The relationship between interoception and stress:

An experience sampling study

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Lay summary

Background

Interoception is the ability to perceive the sensations inside one's body. For example, feeling if your heart is beating fast or if you feel hungry. Interoception is consists of separate dimensions like interoceptive accuracy, which is how good a person is at correctly detecting internal body sensations. Other dimensions of interoception are how much attention is focused on internal body sensations (interoceptive attention), and one's beliefs about their own interoceptive abilities (self-reported interoception), for example how good a person believes they are at detecting internal body sensations or how much attention they believe they direct to internal body sensations. There are important problems in research about interoception. For example, the tasks that are used to measure interoceptive accuracy don't seem to relate to one another, and they also seem to produce false positives and false negatives, meaning that the tasks do not correctly identify how accurate individuals are at perceiving their heartbeats. Similarly, the questionnaires that are used to measure self-reported interoception also don't seem to be related, which suggests that they might be measuring different things. It is also important to mention that there are sex differences in interoception, as women seem to pay more attention to their internal sensations than men but appear to be worse at detecting them correctly.

Interoception is important for physical and mental health because it is linked to abilities that maintain wellbeing like regulating one's emotions. Research suggests that people whose abilities to detect internal body sensations are exceptional or poor, are more likely to experience physical or mental health difficulties. For example, interoception is related to experiencing more stress. However, because of issues measuring interoception, it is difficult to figure out how the relationship between interoception and stress works. This is also complicated by issues measuring stress because stress is a broad term that is used to describe stressful events, the sensations that stress causes in the body, and the experience of long or short-term stress. Therefore, the aim of this study was to explore the relationship between interoception and stress by using better tools and methods. We aimed to do this by completing a thorough review of the literature to decide if there is a consistent relationship between interoception and stress, followed by an empirical study to understand how the relationship works.

First, we completed a review of the published literature to see if there was a relationship between a person's ability to perceive their heartbeats correctly (cardiac interoceptive accuracy) and stress. Because some of the studies didn't directly report the data that we needed, 28 authors were contacted to ask for data and 8 authors provided data from 11 studies. The final sample was 20 studies, which included 29 data points that were compared. Because stress is a multidimensional experience, the comparisons were separated based on the stress measure that studies used: acute physical stressors (physical activities that increase physical stress like exercise), acute cognitive stressors (cognitive activities that increase mental stress like counting backwards), physiological stress response (measures of how stress affects the body like cortisol or heartrate variability) and chronic stress (questionnaire measures of stress). Interoceptive accuracy was measured using the Heartbeat Counting Task (HCT) in all comparisons, which asks participants to count their heartbeats in different time periods. The results suggested that the ability to perceive one's own heartrate is better after being exposed to an acute physical stressor. Having poorer ability to detect heartbeats also seemed to be related to higher levels of both chronic and physiological stress. There was no relationship between acute cognitive stress and the ability to detect heartbeats. Although the results suggested a relationship between cardiac interoceptive accuracy and some dimensions of stress, because of issues with the HCT, which is reported to produce false positives (detects people as being accurate at perceiving their heartbeats when they are not), no strong conclusions can be drawn. There were also not enough studies to complete analyses of sex differences.

The aim of the empirical study was to follow up on the results from the meta-analysis by exploring the relationship between interoception and stress using better tools for measuring both. We did this by using a new task for measuring interoceptive accuracy called the Phase Adjustment Task (PAT), which asks participants to match their heartbeats with tones. To assess individual beliefs about interoception, we used a newly developed questionnaire that measures how good individuals think they are at perceiving different internal sensations, and another questionnaire that measures how much attention individuals think they focus on different internal sensations. We also used a momentary measure of attention to internal sensations, where a mobile phone application prompted participants 10 times daily for 6 days to report how much attention they were paying to internal body sensations or auditory signals (participants were asked to pay attention to either internal or auditory signals to account for the influence of external sensations). Finally, we used multiple measures of stress, including a questionnaire about the experience of stress over the last week, a questionnaire about stressful life events, and recordings of Heartrate Variability (HRV), and we performed a statistical analysis to extract two shared components from the stress measures. We also included in the moment assessments of how stressed participants were feeling and how stressful they thought the situation that they were experiencing was. 117 participants completed the study. The analyses showed that people who believed they paid more attention to internal sensations seemed to be more stressed, and those who believed were better at detecting their sensations seemed to be less stressed. The analyses of momentary measures showed that people who paid more attention to internal sensations also reported feeling more stressed and perceived more situations as stressful. There was no relationship between the ability to detect heartbeats and stress. Interestingly, questionnaire measures and in the moment measures of interoception and stress were not related to each other. We also observed some surprising results as participants who believed that they were better at detecting their internal sensations were less accurate at detecting their heartbeats, which could suggest that individuals have poor knowledge about their own interoceptive abilities. Although these results suggest a relationship between interoception and stress, it is difficult to draw conclusions about the direction of this relationship. Future research could focus on clarifying this relationship by recruiting bigger samples and using different and improved measures.

Investigating the relationship between interoceptive accuracy and stress:

A systematic review and meta-analysis

Abstract

Interoceptive accuracy, the ability to correctly perceive internal body signals such as heartbeats, has been related to processes essential for normal human functioning such as emotion regulation, as well as psychopathology, including stress. However, issues with the measurement of both interoceptive accuracy and stress have led to lack of clarity regarding the relationship between these processes. Given the mixed evidence, this meta-analysis aimed to establish the presence or absence of a relationship between cardiac interoceptive accuracy and different measures of stress separated into four categories - acute physical, acute cognitive, chronic self-report and physiological response. A systematic literature search performed on 13th February 2023 on five databases (PsycINFO Web of Science, PubMed, PsycExtra and PsyArXiv) identified 2014 abstracts. 28 authors were contacted to request data for eligible studies, which yielded a final sample of 20 studies. Results demonstrated relationships between cardiac interoceptive accuracy and facets of stress. Specifically, cardiac interoceptive accuracy showed a positive relationship with acute physical stress, and a negative relationship with self-reported chronic stress and physiological stress response. No significant relationship was observed with acute cognitive stress, however issues with the measurement of stress and interoception preclude strong conclusions regarding observed relationships. Results are discussed in light of issues with the measurement of cardiac interoceptive accuracy and stress.

Introduction

Interoception is defined as the processing of internal body signals (Craig, 2003). One of the main functions of interoceptive systems is to monitor internal physiological signals and adapt behaviour accordingly in order to maintain homeostasis (Craig, 2003). Indeed, interoception has been gaining increasing clinical relevance due to the role it plays in cognitive functions essential for typical functioning such as learning, decision making and emotion processing (Brewer et al., 2021), as well as its association with wellbeing through processes involving self-regulation and the maintenance of homeostasis (Farb et al., 2015). Importantly, interoception is a multi-dimensional construct with various levels of processing across unconscious and conscious levels, though interoceptive accuracy is by far the most commonly assessed facet (Suksasilp & Garfinkel, 2022). According to the multi-dimensional model, interoceptive accuracy refers to the ability to accurately detect or track internal body sensations, as assessed by objective measures of behavioural performance (Suksasilp & Garfinkel, 2022).

Cardiac interoceptive accuracy is the most widely studied domain, while research on other domains such as gastro-intestinal or respiratory sensations remains scarce (Ceunen et al., 2013). Problematically, the relationship between different domains of interoceptive accuracy is mixed, as cardiac interoceptive accuracy appears related to gastric (van Dyck et al., 2016) but not respiratory accuracy (Garfinkel, Manassei, et al., 2016). This may suggest that the perception of different visceral sensations dissociates across domains, or may reflect the different abilities (detection, discrimination, magnitude, etc.) assessed by different interoceptive tasks (Ceunen et al., 2013). The two most widely used measures of cardiac interoceptive accuracy are the heartbeat counting task (HCT), where participants are required to count their heartbeats in a series of time intervals (Schandry, 1981), and the heartbeat discrimination task (HDT), which is often administered using the two-alternative-forcedchoice-format (2AFC), where participants are presented with a series of visual or auditory signals that are presented either with a delay thought to be perceived as synchronous (approximately 200ms), or asynchronous with heartbeats (approximately 550ms; Whitehead et al., 1977). Both measures of cardiac interoceptive accuracy have been subjected to substantial criticism. First, the HCT appears to be influenced by previous knowledge or beliefs about heart rate, making the task liable to false positives (i.e., guessing the number of heartbeats by estimating the time elapsed). Although clear instructions appear to reduce the effects of estimate strategies, relying on participant compliance is problematic (Desmedt et al., 2023). In contrast, the HDT task as commonly administered – using a 2AFC format - has also received criticism, specifically that it may be liable to false negatives (not reporting heartbeats that are present). This is due the observation of differences in the delay at which individuals perceive a signal to be synchronous with their heartbeat (Brener & Ring, 2016). Indeed, there are differences in the delays at which individuals perceive external stimuli to be synchronous with their heartbeat, with some preferring longer and others shorter delays (Brener & Ring, 2016). Hence, the 2AFC HDT might be biased against individuals that perceive external stimuli (auditory or visual) at different delays following the heartbeat than those set by the experimenter as synchronous, resulting in false negatives (Brener & Ring, 2016). More broadly, it should also be noted that whilst ostensibly measuring similar processes, the HCT and HDT are not interchangeable. Indeed, a recent meta-analysis reported that only 4.4% of the variance is shared (Hickman et al., 2020).

Notably, atypical interoceptive abilities, involving either under- or over-perception of internal body signals, appear to be related to a diverse range of physical and mental health conditions, including but not limited to, chronic pain (Di Lernia et al., 2016), autism (Garfinkel, Tiley, et al., 2016), schizophrenia (Ardizzi et al., 2016), obesity (Herbert & Pollatos, 2014), anxiety disorders (Domschke et al., 2010) and depression (Eggart et al., 2019). Another condition related to the development of numerous physical and mental health disorders is stress, a phenomenon that is also thought to be related to interoception (Schulz & Vögele, 2015). Indeed, as will be discussed below, the interaction between stress and interoception might be associated to altered body perception and symptom generation in mental health disorders (Schulz & Vögele, 2015), thus highlighting the importance of better understanding the relationship between interoception and stress.

Stress is an umbrella term broadly used to describe exposure to stressful life events, the experience of chronic stress or the physiological stress response. These different facets of stress are typically associated, although the relationship is complex and influenced by psychological processes such as appraisal, which determine how a stressful situation is perceived by the individual therefore eliciting differences in the stress response (Harkness & Hayden, 2018). Physiologically, there are three systems involved in the stress response: the Sympathetic Adreno-Medullary (SAM) system, the Hypothalamic-Pituitary-Adrenal (HPA) axis and the Autonomic Nervous System (ANS). First, the SAM system provides an initial rapid response to stressors through the release of the catecholamines epinephrine (E) and norepinephrine (NE; Godoy et al., 2018). These facilitate physiological adaptation to acute stress by triggering the fight-or-flight response (Godoy et al., 2018). Second, the HPA axis is the primary neuroendocrine response to stress which modulates biological, cognitive and behavioural responses, and it follows SAM system activation (Lopez-Duran et al., 2020). In response to a stressor, the HPA axis activates the paraventricular nucleus (PVN), leading to the release of adrenocorticotropic hormone (ACTH), which in humans elicits the release of cortisol, an anti-inflammatory hormone that regulates the stress response (Guilliams & Edwards, 2010). Third, the ANS is formed by the Sympathetic Nervous System (SNS) that regulates the fight-or-flight response and the Parasympathetic Nervous System (PNS) involved in rest and recovery processes (Zakreski & Pruessner, 2020). The ANS shows a similar patterns of activation and responds to similar stressors as the HPA axis, with the key differences being that the ANS response tends to be faster and has a shorter duration than the HPA axis activation (Zakreski & Pruessner, 2020).

Different stressors are reported to elicit varying activation of the SAM system, HPA axis and ANS activation. For example physical exercise activates all three systems (Lopez-Duran et al., 2020; Zakreski & Pruessner, 2020), while stressors that include aspects of social evaluation threat or uncertainty appear to be related to the activation of the HPA axis, which increases cortisol levels (Dickerson & Kemeny, 2004). Furthermore, stressors that merely induce negative affective states are not related to HPA axis activation and cortisol release and instead are limited to an initial SAM system activation (Schulz & Vögele, 2015). Additionally, the ANS is reported to respond to other stressors that do not elicit HPA axis activation such as mental effort (Zakreski & Pruessner, 2020). Finally, it is important to highlight the impact of chronic stress on the typical stress response, as chronic exposure to stressors is related to atypical functioning of the HPA axis, characterised by either hyper- or hypo-activation (Guilliams & Edwards, 2010).

Stress is considered to be a multidimensional process involving physiological, psychological and external aspects, making it a notoriously problematic process to define and measure (Harkness & Hayden, 2018). This has important implications for the measurement of stress, as a distinction must be made between exposure to stressors, stress responses which can be physiological or psychological, and whether the stress is acute or chronic (Harkness & Hayden, 2018). Stress responses can be measured via state self-report questionnaires of daily or chronic stress, physiological measures of acute stress or chronic stress such as HRV or cortisol levels respectively, or behavioural responses to acute stressors in laboratory settings (Crosswell & Lockwood, 2020). However, measures corresponding to different levels of the stress response appear to be weakly correlated, which could be indicative of the complexity of the stress response where different responses display overlapping yet distinct processes, as well as methodological limitations of measures (Campbell & Ehlert, 2012).

Despite complexity measuring stress, there is increasing evidence that points to a relationship between interoceptive accuracy and stress. For example, acute stress is related to increased interoceptive accuracy when measured by the HCT, but typically not the HDT (Durlik et al., 2013; for a review see Schulz & Vögele, 2015). A similar pattern is also observed in males using the HDT, but not females, where a decrease in interoceptive accuracy was observed following a stressor (Fairclough & Goodwin, 2007). Likewise, a study investigating the relationship between interoceptive accuracy as measured by the HCT and long term stress reported a negative relationship when long term stress was measured by self-report questionnaires and hair cortisol levels, indicating that increased cardiac interoceptive accuracy might play a role in the early detection of stress symptoms leading to effective self-regulation (Schultchen et al., 2019). Furthermore, a study using the HCT task reported that individuals classified as good heartbeat perceivers showed increased sympathetic activity compared to poor heartbeat perceivers during a mental arithmetic task, but not at baseline, suggesting that higher interoceptive accuracy is associated with greater cardiovascular reactivity to stressful stimuli (Herbert et al., 2010). Similar results were also observed in a study employing two HDT paradigms - the Whitehead and Katkin HDT tasks - where increased cardiac reactivity was observed among good heartbeat perceivers during a mental arithmetic task (Eichler & Katkin, 1994). However, it is important to note that the tasks only appeared to be moderately correlated ($r = 0.41$) and the results did not remain significant when the analysis was separated according to the HDT task employed (Eichler & Katkin, 1994).

One potential explanation for mixed results in the literature regarding interoceptive accuracy and stress relates to the differences between the HCT and HDT, which could be explained by the competition-of-cues model. This model proposes that the increased demand in attentional resources posed by stress could impact performance on the HDT task as it requires the integration of interoceptive and exteroceptive signals, while the HCT task only requires attention to interoceptive signals (Schulz & Vögele, 2015). Evidence of sex differences in the stress response (Fairclough & Goodwin, 2007) and in interoceptive accuracy for both the HCT and HDT tasks (Prentice & Murphy, 2022), also indicate the possibility that effects could be sex specific. However, the exact mechanism linking interoception and stress remains elusive. It may be that the stress response amplifies visceral signals through the activation of the SNS or that attention is directed and focused on those visceral signals, which improves accuracy while decreasing attention to other exteroceptive signals (Schulz & Vögele, 2015).

Another explanation for the mixed results could be related to the measures of stress employed, as research investigating the relationship between interoceptive accuracy and stress has largely focused on the effects of acute stress by employing cognitive stressors such as public speaking tasks (Maeda et al., 2019), planning tasks (Schlinkert et al., 2020) and mental arithmetic tasks (Fairclough & Goodwin, 2007), or physical stressors such as the cold pressor test (CPT; Schulz et al., 2013; Schulz & Vögele, 2015) or physical exercise (Atanasova et al., 2021; Schillings et al., 2021; for a review see Schulz & Vögele, 2015). Problematically, these tasks seem to elicit varying degrees of perceived stress, autonomic response, HPA axis and SAM system activation, which implies that different stressors target distinct aspects of the stress response (Skoluda et al., 2015). Few published studies directly measure how interoceptive accuracy relates to biomarkers or indicators of the physiological stress response such as cortisol or Heart Rate Variability (HRV), and this relationship is only reported in the presence of different acute stressors such as the Trier Social Stress Test (TSST; Maeda et al., 2019) or Socially Evaluated Cold Pressor Test (SECPT; Schaan et al., 2019), which employ stressors reported to activate different facets of the stress response such as the HPA axis or SAM system respectively (Dickerson & Kemeny, 2004; Lopez-Duran et al., 2020). Finally, the absence of studies investigating the relationship between perceived levels of chronic stress and interoceptive accuracy is also notable, with only one study examining this and reporting a negative relationship (Schultchen et al., 2019). This is problematic considering the impact of chronic stress on HPA axis and SAM system activation (Godoy et al., 2018; Lopez-Duran et al., 2020).

Given the mixed results pertaining to the relationship between acute stress and interoceptive accuracy, as well as the lack of studies investigating the relationship between interoceptive accuracy and other dimensions of the stress response such as physiological, behavioural, and chronic self-report measures, there is currently insufficient evidence to draw definitive conclusions about the relationship between interoceptive accuracy and stress. Therefore, the aim of this meta-analysis was to establish the presence or absence of a relationship between interoceptive accuracy and different dimensions of the stress response. Specifically, we reviewed the relationship between different cardiac interoceptive accuracy tasks (HCT and HDT) and measures of stress (acute physical stress, acute cognitive stress, chronic self-reported stress, and physiological stress response). Based on the work of Schulz & Vögele (2015) we predicted a varying relationship between cardiac interoceptive accuracy and stress, expecting a positive relationship between acute stress and interoceptive accuracy (Schulz & Vögele, 2015), and a negative relationship between chronic stress and interoceptive accuracy based on initial results from a recent study (Schultchen et al., 2019). A secondary aim was to investigate the impact of sex (male, female) on the pooled effect sizes given evidence of sex differences (Fairclough & Goodwin, 2007). It was predicted that high interoceptive accuracy scores would be related to lower stress scores in males, with females exhibiting the opposite pattern consistent with previous evidence (Fairclough & Goodwin, 2007).

Method

Search strategy

The systematic review search was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidance (Kudielka & Kirschbaum, 2005). A systematic literature search was performed on 13th February 2023 on the PsycINFO, Web of Science and PubMed databases using the following terms in all search engines: ((“interoception” OR “visceroception” OR “interoceptive”) AND (“awareness” OR “sensation” OR “accuracy” OR “sensitivity” OR “perception” OR “recognition”)) AND “stress”). A search of grey literature was also conducted by entering the same search terms in PsycExtra and PsyArXiv. Finally, a citation search was performed in Google Scholar using the search term “interoceptive cardiac task” to ensure all relevant studies were included in the systematic review.

The search terms were designed to capture all studies that included objective measures of interoceptive accuracy. As previous literature has used the terms ‘sensitivity’, ‘awareness’ and ‘accuracy’ interchangeably to refer to interoceptive accuracy, all terms were included to ensure a comprehensive search. Exercise and other physical activities were not included as a search term to limit the search to studies where exercise was intended as a physical stressor.

The systematic review search yielded 2350 results. Of these, 1,666 were from PsycINFO, 37 from PubMed, 564 from Web of Science, 11 from PsycExtra and 72 from the citation search. Following the removal of 336 duplicates, the final selection was comprised of 2014 articles.

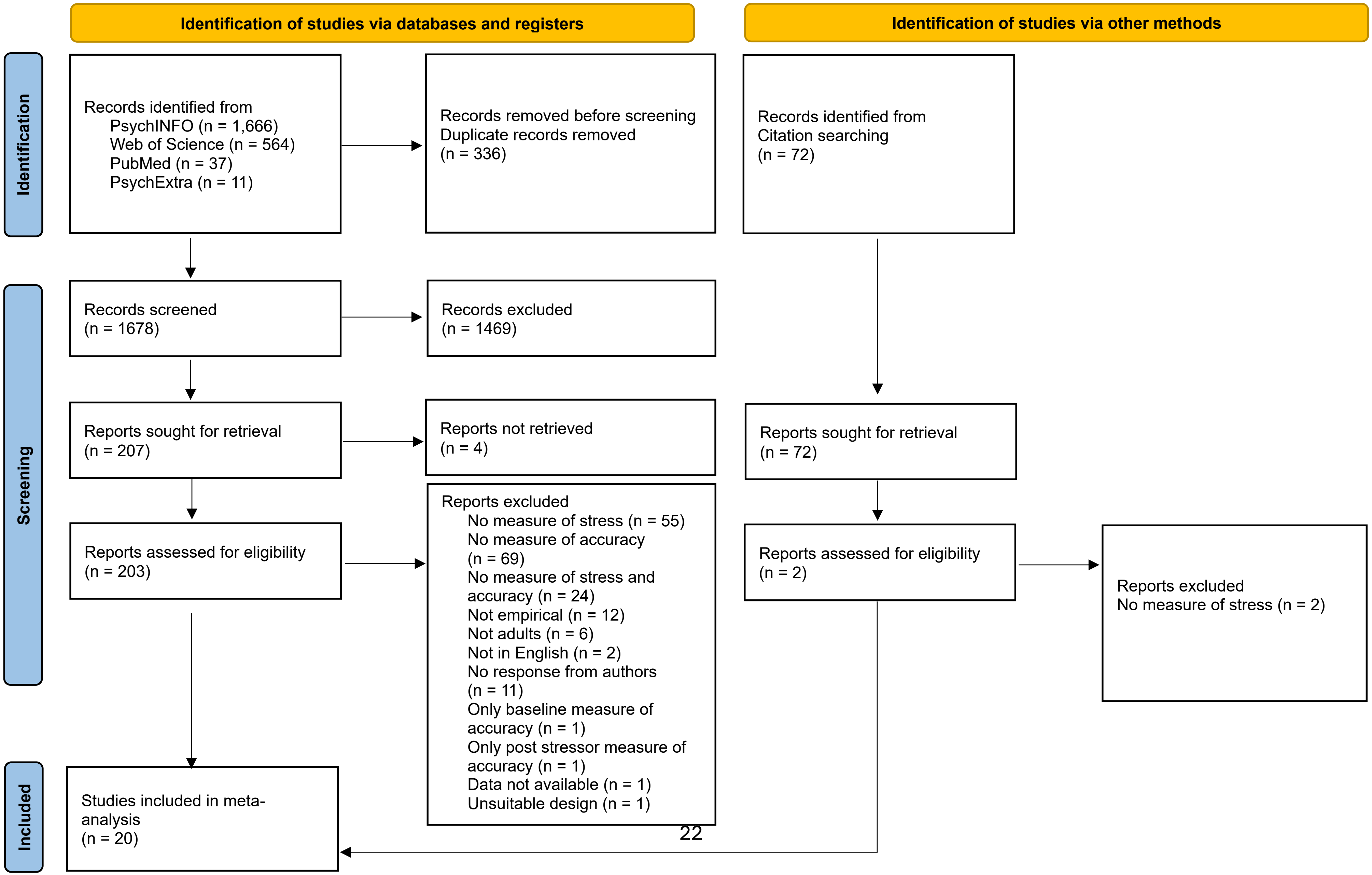
Study selection

The study selection was completed by NI and JM in two stages. First, NI screened all abstracts, and any potentially relevant articles were included for the full text screening. A total of 1805 articles were removed after the abstract screening. The full text screening was completed by NI with the remaining 209 articles, and any articles where there was any ambiguity or uncertainty were also reviewed by JM and discussed. Studies were included in the meta-analysis if they (1) had an experimental design (excluding reviews), (2) employed a human adult sample, (3) were conducted in English, (4) included an objective measure of cardiac interoceptive accuracy, and (5) included a stress measure. Studies were removed if they only included a baseline measure of cardiac interoceptive accuracy before a stressor, but not after the stressor, and no other measures of stress were administered, as we aimed to examine stress induced changes in interoceptive accuracy. 12 studies were excluded due to data being unavailable or authors not replying to data requests. Data was available for two studies, but the sex variable was not coded in one of the studies and the other one only included females, so we were unable to extract the data for sex comparisons from these studies. One further study using the SECPT task was excluded because the HCT post stressor was performed after completing questionnaires, which varied from other studies that administered the HCT immediately after the stressor (Schenk et al., 2020).

The final sample included 20 studies, all of which measured cardiac interoceptive accuracy. Studies that directly reported on the relationship between cardiac interoceptive accuracy and stress were included, as well as studies where authors provided data when not directly reported. A total of 28 authors were contacted and 8 authors were able to provide data for 11 studies. The HCT task was employed in 17 studies, the HDT task in 3 studies and both tasks in 1 study. Figure 1 summarises the number of studies included in each stage and reasons for exclusion. Due to the limited number of studies conducted using the HDT task, the current meta-analysis focuses mainly on results using the HCT task. Authors provided data from 9 studies, which was used for conducting meta-analyses exploring sex differences in the relationship between cardiac interoceptive accuracy and stress.

Figure 1.

Prisma 2020 diagram showing the studies excluded at each stage and reasons for exclusion.



Data Extraction

Relevant data was extracted by one reviewer (NI) and ambiguous studies were verified by a second reviewer (JM). Correlation coefficients (r) were extracted for the relationship between cardiac interoceptive accuracy and stress. T statistic (Cohen's d) and F statistic (partial eta squared, n^2) values were extracted for comparisons of cardiac interoceptive accuracy scores before and after completing a stressor task, and converted into Pearson's correlation coefficient (r) using an online effect size convertor (Lenhard & Lenhard, 2022). For studies that reported more than one measure of stress such as multiple self-report questionnaires or physiological measures, composite scores were calculated by summing all the effect sizes and dividing the sum by the number of effect sizes included to obtain an average. The direction of the effect was adjusted for measures of HRV, where higher scores are indicative of lower stress, by changing the sign of the relationship so for all effect sizes higher scores corresponded to higher stress. The quality of each study was assessed using the quality assessment criteria for assessing quantitative studies (Kmet et al., 2004). Given the small number of studies included in the meta-analysis and the lack of agreement regarding an appropriate cut-off for quality (Hoffmann-Eßer et al., 2018), no studies were excluded based on their quality rating and the quality assessment was only included for descriptive purposes.

Authors were contacted to request data for studies where the effect sizes for the relationship between cardiac interoceptive accuracy and stress (correlations, T- or F- scores) for the whole sample and separately for males and females were not available in the article, supplements, or open online research platforms.

The characteristics and findings of each study included in the meta-analysis are summarised in Tables 1 to 4 below, which have been classified according to the type of stress measure employed. As there was an insufficient number of studies to perform meta-analyses using the HDT task, a table with the characteristics of studies employing the HDT task has been included in Appendix A. Please refer to Appendix B to see the forest and funnel plots of studies using the HDT task.

Table 1.

Characteristics and findings of studies using HCT and acute physical stressors.

Author (year)	N (F/M)	Age (M)	Clinical group	Physical stressor task	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	r	Quality
Atanasova et al. (2021)	70 (38/31)	39.19	IBD	Physical exercise task	High score is better accuracy	High score is more stress	F	2.864	0.201	86%
Schillings et al. (2021)	137 (93/44)	23.7	None	Physical exercise task and Yoga	High score is better accuracy	High score is more stress	n^2	0.029	0.170	92%
Williams et al. (2020)	53 (44/9)	37.45	FND	CPT	High score is better accuracy	High score is more stress	n^2	0.16	0.4	100%
Schulz et al. (2013)	42 (29/13)	22.95	None	SECPT	High score is better accuracy	High score is more stress	n^2	0.16	0.4	83%
Schaan et al. (2019)	66 (45/21)	25	None	SECPT	High score is better accuracy	High score is more stress	d	0.235	0.117	79%

Abbreviations: ES Effect Size, r Pearson's correlation coefficient, IBD Irritable Bowel Disease, FND Functional Neurological Disorder, CPT Cold Pressor Test, SECPT Socially Evaluated Cold Pressor Test, F ANOVA F-value, n^2 partial eta squared, d Cohen's d.

Table 2.

Characteristics and findings of studies using HCT and acute cognitive stressors.

Author (year)	N (F/M)	Age (M)	Clinical group	Cognitive stressor task	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	r	Quality
Wittkamp et al. (2018)	59 (40/19)	23.4	None	CRTT	High score is better accuracy	High score is more stress	n^2	0.05	0.224	85%
Maeda et al. (2019)	36 (20/16)	21.7	None	TSST	High score is better accuracy	High score is more stress	t	-0.976	-0.161	95%
Schulz et al. (2013)	42 (29/13)	22.95	None	SECPT	High score is better accuracy	High score is more stress	n^2	0.16	0.4	83%
Schaan et al. (2019)	66 (45/21)	25	None	SECPT	High score is better accuracy	High score is more stress	d	0.235	0.117	79%

Abbreviations: ES Effect Size, r Pearson's correlation coefficient, CRTT Choice Reaction Time Task, TSST Trier Social Stress Test, SECPT Socially Evaluated Cold Pressor Test, n^2 partial eta squared, t Student's t-distribution, d Cohen's d.

Table 3.

Characteristics and findings of studies using the HCT task and chronic self-report stress measures.

Author (year)	N (F/M)	Age (M)	Clinical group	Questionnaire	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	Composite ES	Quality
Agostinho et al. (2019)	60 (31/29)	23.63	None	PSS	High score is better accuracy	High score is more stress	r	-0.119	-0.119	86%
Millon et al. (2021)	35 (35/0)	45	HIV	PSS	High score is better accuracy	High score is more stress	r	0.033	0.033	86%
Valenzuela-Moguillansky et al. (2017)	59 (59/0)	45.15	FM	DASS	High score is better accuracy	High score is more stress	r	-0.184	-0.184	91%
Schultchen et al. (2019)	98 (50/48)	23.63	None	Screening scale of TICS	High score is better accuracy	High score is more stress	r	-0.28	-0.198	82%
				Uncertainty (SCI)	High score is better accuracy	High score is more stress	r	-0.19		
				Excessive demands (SCI)	High score is better accuracy	High score is more stress	r	-0.19		

				Stress symptoms (SCI)	High score is better accuracy	High score is more stress	r	-0.24		
				Negative events (SCI)	High score is better accuracy	High score is more stress	r	-0.09		
Murphy et al. (2018)	287 (201/86)	38.07	None	DASS	High score is better accuracy	High score is more stress	r	-0.285	-0.285	82%
Rost et al. (2017)	98 (76/22)	45.2	FM	DASS	High score is better accuracy	High score is more stress	r	0.11	0.11	91%
Lima-Araújo et al. (2022)	40 (20/20)	24.15	None	PSS	High score is better accuracy	High score is more stress	r	0.097	0.097	95%
Tabor et al. (2019)	38 (19/19)	23	AS	Stress response (BPQ)	High score is better accuracy	High score is more stress	r	-0.52	-0.227	75%
				Autonomic Nervous System Reactivity (BPQ)	High score is better accuracy	High score is more stress	r	0.067		
Schulz et al. (2013)	42 (29/13)	22.95	None	TICS	High score is better accuracy	High score is more stress	r	-0.1	-0.1	83%

Schenk et al. (2020)	73 (50/23)	22.73	None	Work overload (TICS)	High score is better accuracy	High score is more stress	r	0.119	-0.058	83%
				Social overload (TICS)	High score is better accuracy	High score is more stress	r	0.05		
				Pressure to perform (TICS)	High score is better accuracy	High score is more stress	r	0.009		
				Work discontent (TICS)	High score is better accuracy	High score is more stress	r	-0.177		
				Excessive demands at work (TICS)	High score is better accuracy	High score is more stress	r	-0.107		
				Lack of social recognition (TICS)	High score is better accuracy	High score is more stress	r	-0.087		
				Social tensions (TICS)	High score is better accuracy	High score is more stress	r	-0.093		
				Social isolation (TICS)	High score is better accuracy	High score is more stress	r	-0.102		

				Chronic worrying (TICS)	High score is better accuracy	High score is more stress	r	-0.136		
Schulz et al. (2022)	114 (56/58)	36.1	MDD	CTQ	High score is better accuracy	High score is more stress	r	-0.05	-0.05	86%

Abbreviations: ES Effect Size, HIV Human Immunodeficiency Virus, FM Fibromyalgia, AS Anxiety Sensitivity, PSS Perceived Stress Scale, DASS Depression Anxiety Stress Scale, TICS Trier Inventory for the Assessment of Chronic Stress, SCI Stress and Coping Inventory, BPQ Body Perception Questionnaire, CTQ Childhood Trauma Questionnaire, r Pearson's correlation coefficient.

Table 4.

Characteristics and findings of studies using HCT and physiological stress response measures.

Author (year)	N (F/M)	Age (M)	Clinical group	Physiological measure	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	r	Adjusted r	Composite ES	Quality
Herbert et al. (2010)	38 (19/19)	26.3	None	HFnu	High score is better accuracy	High score is less stress	t	-0.17	-0.026	0.026	-0.009	77%
				HF	High score is better accuracy	High score is less stress	t	0.29	0.045	-0.045		
Gomes da Silva Machado et al. (2019)	32 (32/24)	24	None	RR interval	High score is better accuracy	High score is less stress	r	0.42	0.42	-0.42	-0.42	86%
Maeda et al. (2019)	36 (20/16)	21.7	None	Salivary cortisol	High score is better accuracy	High score is more stress	r	-0.142	-0.142	-0.142	-0.142	95%
Lima-Araujo et al. (2022)	40 (20/20)	24.15	None	Plasma Cortisol	High score is better accuracy	High score is more stress	r	-0.026	-0.026	-0.026	-0.026	95%
Rost et al. (2017)	98 (76/22)	45.2	FM	RMSSD	High score is better accuracy	High score is less stress	r	0.142	0.142	-0.142	-0.127	91%

				pNN50	High score is better accuracy	High score is less stress	r	0.112	0.112	-0.112		
Tabor et al. (2019)	38 (19/19)	23	AS	HRV	High score is better accuracy	High score is less stress	r	0.175	0.175	-0.175	-0.175	75%
Schultchen et al. (2019)	98 (50/48)	23.63	None	Cortisol/DHEA ratio	High score is better accuracy	High score is more stress	r	-0.21	-0.21	-0.22	-0.085	82%
				Hair cortisol	High score is better accuracy	High score is more stress	r	0.05	0.05	0.05		
Williams et al. (2020)	53 (44/9)	37.45	FND	Cardiosympathetic index	High score is better accuracy	High score is less stress	r	-0.57	-0.57	0.57	0.043	100%
				Cardiovagal index	High score is better accuracy	High score is less stress	r	0.483	0.483	-0.483		
Schenk et al. (2020)	73 (50/23)	22.73	None	Cortisol	High score is better accuracy	High score is more stress	r	-0.262	-0.262	-0.262	-0.262	83%

Abbreviations: ES Effect Size, r Pearson's correlation coefficient, FM Fibromyalgia, FND Functional Neurological Disorder, HFnu High Frequency powers of heart rate variability expressed in normal units, HF High-Frequency power, RMSSD Root Mean Square of Successive

Differences between normal heartbeats, pNN50 mean number of times an hour in which the change in successive normal sinus intervals exceeds 50 milliseconds, HRV Heart Rate Variability, DHEA dehydroepiandrosterone, t Student's t-distribution.

Measures used

Interoceptive accuracy measures

As evidence suggests that HCT and HDT tasks are not interchangeable (Hickman et al., 2020), studies were included in different meta-analyses depending on the task of cardiac interoceptive accuracy used. Heart rate was calculated using Electrocardiogram (ECG) recordings for most studies. One study used an electroencephalography (EEG) to record heart rate (Lima-Araujo et al., 2022), another study used a pulse oximeter with a soft finger sensor (Maeda et al., 2019), one study employed a smartphone application that uses a camera-driven photoplethysmogram sensor to detect heart beats when participants placed their finger over a smartphone camera (Plans et al., 2021), and three studies employed a polar watch which is a less invasive measure that is reported to have comparable validity and reliability to ECG recordings (Schillings et al., 2022; Schultchen et al., 2019; Tabor et al., 2019).

The HCT requires participants to count their heartbeats in different time intervals and report them to the experimenters. Three to six trials were completed in all studies, with the length and order of intervals varying between studies. Two studies included a 10 second initial training interval for participants to familiarise with the task (Schillings et al., 2021; Schultchen et al., 2019), one study included a 15 second practice trial (Williams, 2018), another study included a 20 second practice trial (Schenk et al., 2020) and two studies included a 25 second practice trial (Rost et al., 2017; Wittkamp et al., 2018). One study also reported offering practice trials to participants, but the total number and duration of such trials were not explicitly reported (Machado et al., 2019).

Heartbeat perception accuracy was calculated using different variations of the following formula for all studies:

$$\text{Interoceptive accuracy} = \frac{1}{\text{trials}} \sum \left(1- \frac{\text{recorded heart beats} - \text{reported heart beats}}{\text{recorded heart beats}}\right)$$

Thus, most scores ranged from 0 to 1, with 1 indicating absolute accuracy. The only exceptions were two studies that reported the results from 0 to 100 instead, with scores close to 100 indicating higher accuracy (Machado et al., 2019; Murphy et al., 2018). Millon and Shors (2021) also used an alternative calculation for one participant who consistently overestimated their heart rate:

$$\text{Interoceptive accuracy} = 1 - \frac{\text{recorded heart beats} - \text{reported heart beats}}{\left(\frac{\text{recorded heart beats} + \text{reported heart beats}}{2}\right)}$$

Information about the HDT task and calculations included in supplementary meta-analyses are summarised in Appendix B.

Stress measures

Given that stress is a multidimensional process, for the purposes of this meta-analysis and based on previous research, stress measures were classified into four distinct categories.

First, when conceptualising stress, a key distinction must be made between external events or stressors and internal responses to stress (Wright et al., 2020). Therefore, measures were initially classified as either stressor tasks or measures of the stress response. Stressor tasks were further classified into either physical or cognitive stressors, as these can result in different stress responses and engagement of neural networks (Godoy et al., 2018; Budde et al., 2010; Martin et al., 2024). Studies employing the Socially Evaluated Cold Pressor Test (SECPT), which includes components of both physical and psychological stress, were included in both acute physical and cognitive stress meta-analyses.

Measures of stress response were further divided into measures of psychological processes such as chronic stress, and measures of the physiological stress response involving the HPA axis or ANS activation. Psychological processes included self-report questionnaires of perceived stress, while the physiological stress response consisted of measures of Heart

Rate Variability (HRV) and cortisol. Table 5 summarises the stress measures included in the meta-analysis.

Table 5.

Summary of stress measures detailing their relationship to stress as well as a description of measurement method.

Stress measure	Type	Relationship to stress	Measurement	Study
Physical exercise task	Acute physical stressor	Physical exercise activates the stress system which involves the sympathetic nervous system and the HPA axis (Mastorakos et al., 2005).	Participants were asked to perform 10 squats to induce alterations to the cardiovascular homeostasis.	Atanasova et al. (2021)
Yoga	Acute physical stressor	Physical exercise activates the stress system which involves the sympathetic nervous system and the HPA axis (Mastorakos et al., 2005).	2 minutes of jumping to warm up followed by a 20-minute Yoga session that consisted of two rounds of six consecutively performed instructed asanas (i.e., Warrior I, Chair, Cobra, and Dolphin Pose).	Schillings et al. (2021)
Endurance task	Acute physical stressor	Physical exercise activates the stress system which involves the sympathetic nervous system and the HPA axis (Mastorakos et al., 2005).	2 minutes of jumping to warm up followed by two rounds of nine different stepper exercises (each one lasting one minute).	Schillings et al. (2021)
Cold Pressor Test (CPT)	Acute physical stressor	The CPT was originally developed to increase blood pressure and it elicits a strong physiological response (Lovallo, 1975).	Participants immersed their left hand into cold water above the wrist for as long as possible (but up to three minutes). The procedure was repeated three times, in 30 second intervals.	Williams et al. (2020)

Trier Social Stress Test (TSST)	Acute cognitive stressor	The TSST is the gold standard for the assessment of acute stress in laboratory conditions. The key components that trigger HPA axis activations are reported to be a combination of social-evaluative threat and uncontrollability, both of which are present in the TSST (Allen et al., 2016).	Participants were instructed to prepare a speech for 10 minutes, after which they delivered a speech for 5 minutes, which was followed by performing a mental arithmetic task for another 5 minutes.	Maeda et al. (2019)
Choice Reaction Time Task (CRTT)	Acute cognitive stressor	Heart rate measurements taken before, during and after the CRTT showed a significant increase in heart rate during the task, compared to baseline and after completing the task (Wittkamp et al., 2018).	Participants were presented with a light bulb flashing randomly in one of five colours (white, blue, yellow, red, green) and instructed to press the button with the corresponding colour as accurately and as fast as possible.	Wittkamp et al. (2018)
Socially Evaluated Cold Pressor Test (SECPT)	Acute cognitive and physical stressor	The combined administration of a physiological and psychological stressor has been reported to increase sympathetic nervous system and HPA axis activation (Minkley et al., 2014).	Participants were instructed to immerse their hand in cold water (0 – 4°C) for three minutes by an experimenter unknown to them who was wearing a white lab coat. They were also instructed to look at a camera that would record their facial expressions during the task.	Schaan et al. (2019)
			Participants were instructed to immerse their left hand for 3 minutes into a container with either cold (0 – 3◦C) or warm water (32 – 35 ◦ C) in the presence of an experimenter of the opposite sex and a fake camera.	Schulz et al. (2013)

			Participants were instructed by a researcher wearing a white coat to immerse their hand in ice water (0 – 3◦C) for three minutes. During that time a fake camera was introduced to monitor their facial expressions. If they removed their hand early, participants were told others were able to continue for longer.	Schenk et al. (2020)
Trier Inventory for the Assessment of Chronic Stress (TICS)	Self-report measure	The TICS questionnaire is reported to have adequate reliability (0.78 – 0.89; M_r = 0.83) and correlates with physiological markers of stress, such as high salivary cortisol (Schulz et al., 2013). The TICS questionnaire consists of 57 items rated on a 5-point Likert scale ranging from 1 = never to 5 = always.	Participants were presented with 57 items belonging to 9 scales: Work Overload, Social Stress, Pressure to Succeed, Work Discontent, Excessive Demands, Lack of Social Acceptance, Social Strain, Social Isolation, and Chronic Worries.	Schulz et al. (2013)
			The TICS questionnaire was administered on day 1 of testing, in the 30 minutes following the stressor task (SECPT). The German version of the TICS was administered, and a composite score of the following nine subscales was calculated: Work Overload, Social Stress, Pressure to Succeed, Work Discontent, Excessive Demands, Lack of Social Acceptance, Social Strain, Social Isolation, and Chronic Worries.	Schenk et al. (2020)

The Screening Scale of TICS	Self-report measure	The screening scale consists of 12 items rated on a 5-point Likert scale ranging from 0 = never to 4 = very often.	The screening scale of the TICS is reported to have excellent internal consistency of α = 0.91 (Schultchen et al., 2019). Higher values indicate a greater chronic stress level.	Schultchen et al. (2019)
Perceived Stress Scale (PSS)	Self-report measure	The PSS is a self-report measure of psychological stress which measures "the degree to which individuals appraise situations in their lives as stressful" (Lee, 2012). The scale consists of 14 items rated on a 5-point Likert scale from 0 = never to 4 very often. The PSS is reported to have good internal consistency (α > 0.70) and test-retest reliability (Lee, 2012).	Participants completed the Portuguese validated measure, which has been deemed adequate.	Agostinho et al. (2019)
			Participants completed the 10 item version of the PSS, which is reported to have good internal consistency (α > 0.70) and test-retest reliability (Lee, 2012).	Millon et al. (2021)
			The 14-item version of the PSS was administered to participants which is reported to have good internal consistency (α = 0.83).	Lima-Araújo et al. (2022)

Depression Anxiety and Stress Scale (DASS) Stress subscale	Self-report measure	The DASS-21 stress subscale consists of 7 items rated on a 4-point Likert scale from 0 = never to 4 = almost always. The DASS-21 stress subscale has been reported to have acceptable internal consistency (α = 0.84; Sinclair et al., 2012).	Participants completed the Spanish validated version of the DASS-21 for a Chilean population, which is reported to have excellent internal consistency (α = 0.91; Antúnez & Vinet, 2012)	(Sinclair et al., 2012)
			Participants completed the English version of the DASS-21 questionnaire.	Murphy et al. (2018)
			Participants completed the 42-item version of the DASS questionnaire which was reported to have excellent internal consistency for the stress subscale within their sample (α = 0.95).	Rost et al. (2017)
			Participants completed the English version of the DASS-21 questionnaire in Qualtrics.	Plans et al. (2021)
Stress and Coping Inventory (SCI)	Self-report measure	The SCI is a self-report measure of stressful experiences, as well as physical and psychological symptoms of stress. Four subscales were administered, each consisting of 7 items rated on a 7-point Likert scale from 1 = no strain to 7 = very high strain. Internal consistency was good for uncertainty (α = 0.78) and the physical and psychological symptoms subscales (α = 0.86), and acceptable for the excessive demands and negative events subscales (α = 0.69; Schultchen et al., 2019).	Participants completed three subscales for stress experiences (uncertainty, excessive demands, and negative events) and the subscale for physical and psychological symptoms online.	Schultchen et al. (2019)

Body Perception Questionnaire (BPQ) - Stress response subscale	Self-report measure	The BPQ stress response subscale consists of 10 items rated on a 5-point Likert scale from 1 = never to 5 always, where participants are asked to imagine themselves in a very stressful situation and rate their awareness of perceived changes due to stress (Porges, S. W, 1993)	Participants completed the stress response subscale of the BPQ during the second testing session.	Tabor et al. (2019)
Body Perception Questionnaire (BPQ) - Autonomic Nervous System Reactivity	Self-report measure	The BPQ Autonomic Nervous System Reactivity subscale consists of 26 items rated 5-point Likert scale from 1 = never to 5 always, where participants were asked to rate statements regarding their cardiovascular, respiratory, digestive, and temperature regulation systems (Porges, 1993).	Participants completed the autonomic nervous system reactivity subscale of the BPQ during the second testing session.	Tabor et al. (2019)
Child Trauma Questionnaire (CTQ)	Self-report measure	The CTQ is a self-report measure about childhood trauma consisting of 28 items rated on a 5-point Likert scale from 1 = never true to 5 = very often true. Early life stress as measured with the CTQ is reported to relate to alterations in stress reactivity in later life through sympathetic nervous system and HPA axis dysfunction (Pechtel & Pizzagalli, 2011).	A German version of the CTQ was administered a day prior to testing.	Schulz et al. (2022)
Heart Rate Variability (HRV)	Physiological stress response	HRV variables have been reported to change in response to stress induced using different methods (Kim et al., 2018).	HRV was derived from the Interbeat Interval (IBI) measured with an Electrocardiogram (ECG) during the heartbeat detection task.	Fairclough et al. (2007)

			Heart rate data was recorded using a Polar V800 Watch during the heartbeat counting task. Participants completed a baseline session and a test session 24 hours after and wore the watch for the duration of both sessions.	Tabor et al. (2019)
RR interval	Physiological stress response	Increases of stress are associated to decreases in RR interval (Kim et al., 2018).	RR interval was measured using an ECG recording at rest, before engaging in any physical activity.	Gomes da Silva Machado et al. (2019)
Root Mean Square of Successive Differences (RMSSD)	Physiological stress response	Reductions of RMSSD have been consistently associated with stress, and there is evidence that supports the use of RMSSD as a metric of stress (Kim et al., 2018).	Interbeat intervals were downloaded from the polar watch and HRV analyses were performed using the ARTiiFACT software. RMSSD was measured at baseline.	Rost et al. (2017)
			Beat to beat intervals were extracted from the photoplethysmograph software and analysed using the RHRV package in R. Core time domain methods from the beat-to-beat interval were employed to calculate time analysis statistics such as RMSSD.	Plans et al. (2021)

Standard deviation of the NN interval (SDNN)	Physiological stress response	SDNN is a time domain measure of HRV, and it is reported to be the index of physiological resilience against stress (Kim et al., 2018).	Beat to beat intervals were extracted from the photoplethysmograph software and analysed using the RHRV package in R. Core time domain methods from the beat-to-beat interval were employed to calculate time analysis statistics such as SDNN.	Plans et al. (2021)
Proportion of successive NN intervals greater than 50 derived by the number of NN intervals (pNN50)	Physiological stress response	pNN50 is a time domain measure of HRV. pNN50 is associated to the Parasympathetic nervous system, and it reflects beat to beat changes (Kim et al., 2018).	Beat to beat intervals were extracted from the photoplethysmograph software and analysed using the RHRV package in R. Core time domain methods from the beat-to-beat interval were employed to calculate time analysis statistics such as pNN50.	Plans et al. (2021)
			Interbeat intervals were downloaded from the polar watch and HRV analyses were performed using the ARTiiFACT software. pNN50 was measured at baseline to reflect of parasympathetic control over heart rate.	Rost et al. (2017)
High Frequency normalised units (HFnu) band of HRV	Physiological stress response	Hfnu is the normalised unit of HF power, which has been shown to minimise changes in the total power of HF (Herbert et al., 2010).	ECG data at baseline was used to estimate RR intervals which were imported to a heart rate analysis program to calculate HFnu.	Herbert et al. (2010)
High Frequency (HF) band of HRV	Physiological stress response	HF is the high frequency domain of HRV and is associated with parasympathetic nervous system and vagal activity. Higher HF is associated with physiological relaxation and recovery.	ECG data at baseline was used to estimate RR intervals which were imported to a heart rate analysis program to calculate HF.	Herbert et al. (2010)

Cardiosympathetic index	Physiological stress response	The cardiosympathetic index is a method for analysing RR intervals using Lorenz plots which appears to be more sensitive to sympathetic changes than analysing the coefficient of variation using standard deviations and means (Toichi et al., 1997).	RR intervals were recorded during an ECG at baseline. A non-linear technique for assessing cardiac autonomic function was employed, which involved the construction of a Lorenz plot where the variation in RR intervals was presented with two axes: a Longitudinal axis (L) and a transverse axis (T). The cardiosympathetic index was calculated as L/T.	Williams et al. (2020)
Cardiovagal index	Physiological stress response	The cardiovagal index is a method for analysing RR intervals using Lorenz plots which is sensitive to parasympathetic changes than analysing the coefficient of variation using standard deviations and means (Toichi et al., 1997).	RR intervals were recorded during an ECG at baseline. A non-linear technique for assessing cardiac autonomic function was employed, which involved the construction of a Lorenz plot where the variation in RR intervals was presented with two axes: a Longitudinal axis (L) and a Transverse axis (T). The cardiovagal index was calculated as log10 (T x L).	Williams et al. (2020)
Cortisol/DHEA ratio	Physiological stress response	Cortisol measurement was supported to be a biomarker of chronic stress by nine studies in a recent meta-analysis (Noushad et al., 2021). There is early evidence to suggest that Cortisol/DHEA ratio increases under acute and prolonged psychological stress (Izawa et al., 2012).	2 cm of hair was analysed for cortisol and DHEA. This sample provided information on participants' stress levels over an approximate period of 2 months prior to testing.	Schultchen et al. (2019)

Hair cortisol	Physiological stress response	Cortisol measurement was supported to be a biomarker of chronic stress by nine studies in a recent meta-analysis (Noushad et al., 2021). Hair cortisol is a measure of long-term exposure to stress, with 1 cm of hair closest to the scalp reflecting the cortisol levels over the past two months (Iqbal et al., 2023).	2 cm of hair was analysed for cortisol and DHEA. This sample provided information on participants' stress levels over an approximate period of 2 months prior to testing.	Schultchen et al. (2019)
Salivary cortisol	Physiological stress response	Both psychological and physical stress activate the HPA axis which releases cortisol hormones in the body. Cortisol measurement was supported to be a biomarker of chronic stress by nine studies in a recent meta-analysis (Noushad et al., 2021). Salivary cortisol is the most used measure of cortisol in research as a non-invasive measure of endocrinological stress (Iqbal et al., 2023). Salivary cortisol appears to be mostly positively associated to perceived stress (Iqbal et al., 2023).	Participants were asked to salivate for 2 minutes and drool into a specimen tube through a 4 cm long straw. Salivary cortisol was measured at 4 different time points. Baseline salivary cortisol levels were included in this meta-analysis.	Maeda et al. (2019)

			Six samples of participant saliva were collected, one at baseline and five more after a stressor (SECPT). An average of these samples was used in statistical analyses.	Schenk et al. (2020)
Plasma cortisol	Physiological stress response	Cortisol measurement was supported to be a biomarker of chronic stress by nine studies in a recent meta-analysis (Noushad et al., 2021). Plasma cortisol appears to be mostly positively associated to perceived stress, although some of the results appear to be contradictory (Iqbal et al., 2023).	Blood samples were collected by venipuncture on the first and third days of the experiment between 8 and 9 am after 45 minutes of resting. Participants were instructed to avoid caffeine consumption.	Lima-Araújo et al. (2022)

Analysis strategy

All analyses were performed using R version 4.3.0 (Posit team, 2023), and the devtools (Wickham et al., 2022), dmetar (Harrer et al., 2019), meta (Schwarzer, 2007) and tidyverse (Wickham et al., 2019) packages. Effect sizes were pooled using the 'metacor' function in the meta package.

Due to the multiple stress measures and populations included in the meta-analysis, heterogeneity in the data was assumed. Thus, random effect models were used to calculate pooled effect sizes and the conservative Sidik Jonkman estimator was applied, as it is reported to be accurate when heterogeneity is moderate to large (Harrer et al., 2022a; Sidik & Jonkman, 2007). A test of heterogeneity was conducted, and Q and I^2 statistics were reported for each meta-analysis. I^2 was interpreted following the 'rule of thumb' where 25% is interpreted as low, 50% as moderate and 75% as high heterogeneity (Harrer et al., 2022a). Publication bias was assessed with funnel plots that show the relationship between Fisher's z transformed correlation and standard error, and Eggers' regression test was reported for meta-analyses that included more than 10 studies, as including fewer studies would yield insufficient statistical power to detect asymmetry (Harrer et al., 2022b).

Results

Acute Physical Stress

A total of five effect sizes were pooled, resulting in a significant positive pooled effect size of $r = 0.241$ (0.106 – 0.368; $p = 0.001$), indicating that acute physical stress is related to improved cardiac interoceptive accuracy. Between study heterogeneity was estimated as low as evidenced by a non-significant Q value of 4.64 ($p = 0.327$), $T^2 = 0.01$ and $I^2 = 13.7\%$. Figure 2 shows individual effect sizes from each study. No outliers were identified at 95% Confidence Interval (CI), as observed by the forest plot where all individual effect sizes overlap the pooled effect size (Figure 2). An influence analysis using the leave-one-out method demonstrated effect sizes ranging from 0.20 to 0.27, all of which were significant indicating that individual studies did not substantially influence the pooled effect size. There was an insufficient number of studies to perform Eggers' test to assess publication bias, but the slight asymmetry observed in the funnel plot might be suggestive of publication bias (Figure 3).

Figure 2.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of acute physical stress.

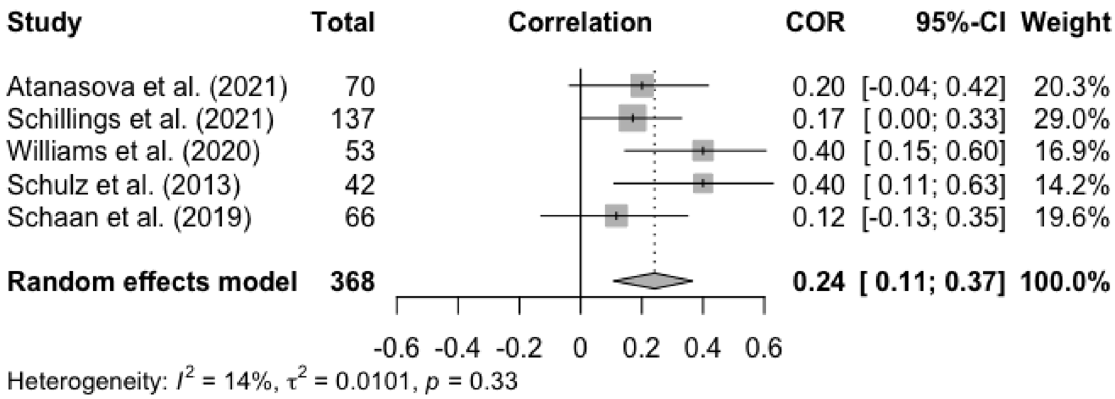
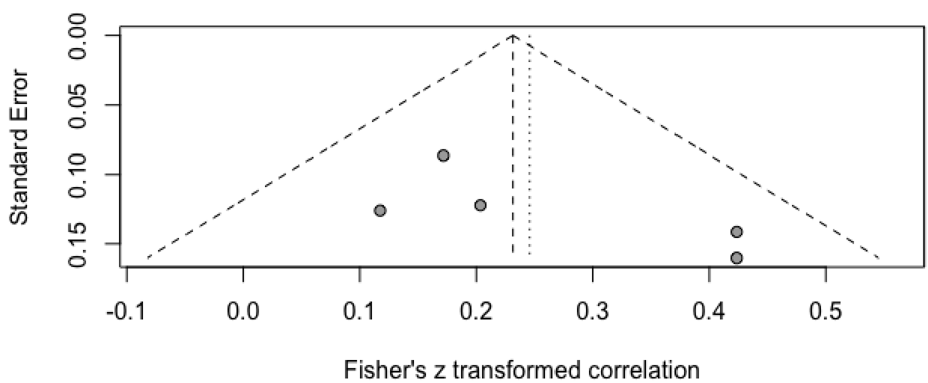


Figure 3.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of acute physical stress.

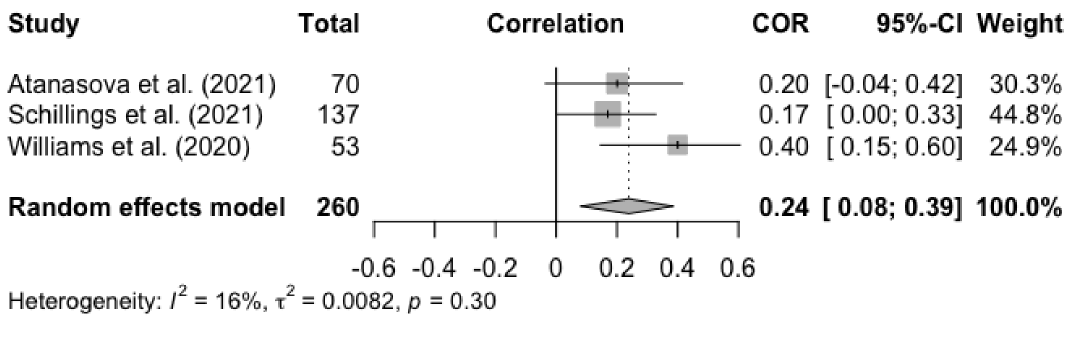


A sub-analysis was completed after removing studies using the SECPT[1] task by pooling the effect sizes of three studies, which resulted in a significant pooled effect size of r = 0.239 (0.08 – 0.39; p = 0.004). A Q value of 2.38 (p = 0.305), T^2 = 0.008 and I^2 = 15.9% indicated that between study heterogeneity was low. No significant outliers were identified at 95% CI as observed by the forest plot (Figure 4). There was an insufficient number of studies to perform Eggers' test, but the funnel plot asymmetry observed in Figure 5 is indicative of publication bias. Finally, an influence analysis using the leave-one-out method demonstrated a range of significant effect sizes ranging from 0.18 to 0.29, indicating that individual studies did not substantially influence the pooled effect size.

There was an insufficient number of studies employing the HDT task and a physical stressor to run a meta-analysis.

Figure 4.

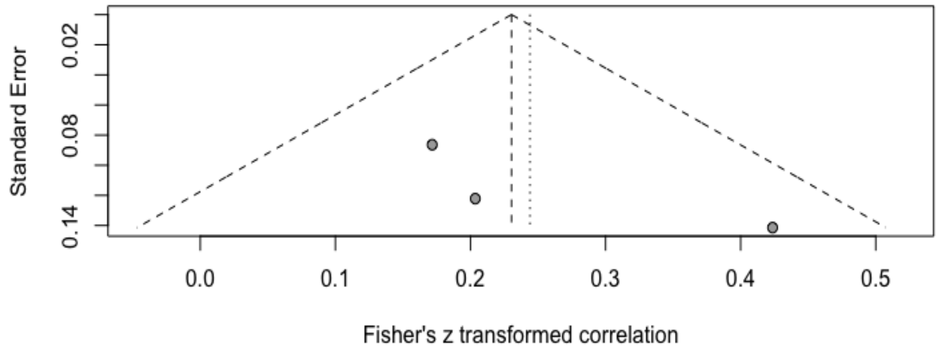
Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of acute physical stress without SECPT.



[1] Studies including the SECPT task were removed from the analysis to isolate physical stress as the SECPT includes both acute physical and cognitive stress components.

Figure 5.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of acute physical stress without SECPT.



Acute Cognitive Stress

The relationship between cardiac interoceptive accuracy and acute cognitive stress was non-significant for the four pooled effect sizes r = 0.156 (-0.08 – 0.376; p = 0.156). Individual effect sizes from each study are shown in Figure 6. There was an insufficient number of studies to perform Eggers' test, but the funnel plot symmetry (Figure 7) is suggestive of no publication bias. Between study heterogeneity was estimated to be T^2 = 0.037, which consistent with a non-significant Q test (Q = 6.51; p < 0.089) and an I^2 value of 53.9% are indicative of moderate heterogeneity. No outliers were identified that significantly deviated from the 95% CI as demonstrated by the forest plot (Figure 6). Influence analyses of the total sample using the leave-one-out method demonstrated a range of non-significant effect sizes ranging from 0.08 to 0.24, and one significant effect size, indicating that the pooled effect size was influenced by individual studies.

Figure 6.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of acute cognitive stress.

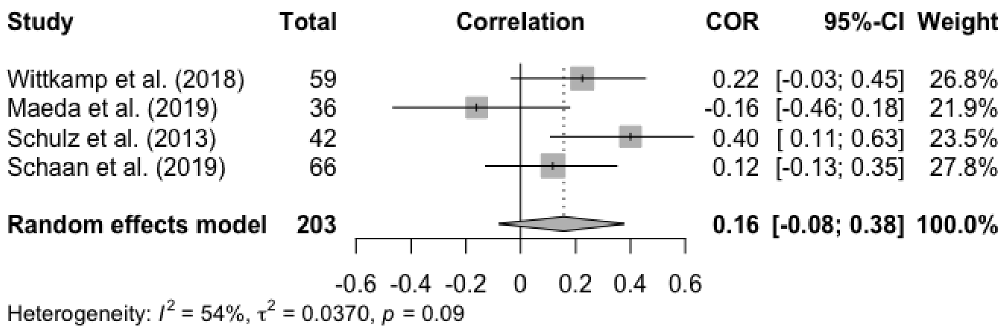
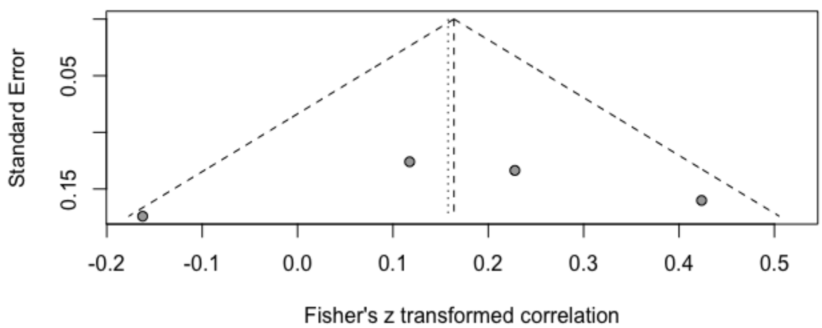


Figure 7.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of acute cognitive stress.



A sub-analysis was completed after removing studies using the SECPT[2] task by pooling the effect sizes of two studies, which resulted in a non-significant pooled effect size (r = 0.05 (-0.307 – 0.394), p = 0.79), and moderate heterogeneity as evidenced by a Q value of 3.16 (p = 0. 075), T^2 = 0.047, and I^2 = 68.4%. No significant outliers were identified at 95% CI as observed by the forest plot (Figure 8). There was an insufficient number of studies to perform Eggers' test, but the funnel plot asymmetry observed in Figure 9 is indicative of publication bias. Influence analyses using the leave-one-out method yielded effect sizes

[2] Studies including the SECPT task were removed from the analysis to isolate cognitive stress as the SECPT includes both acute physical and cognitive stress components.

ranging from -0.16 to 0.22, one of which was non-significant indicating that individual studies substantially influenced the pooled effect size.

Figure 8.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of acute cognitive stress without SECPT.

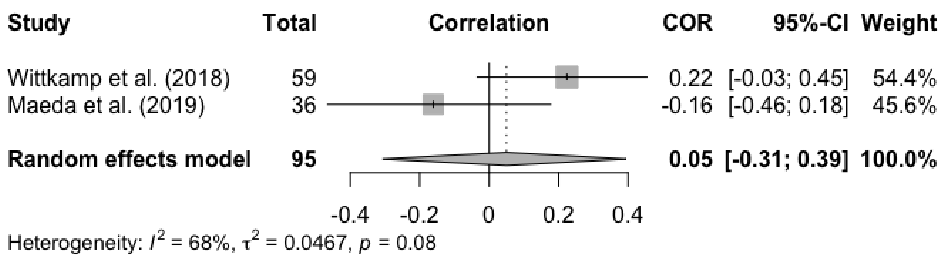
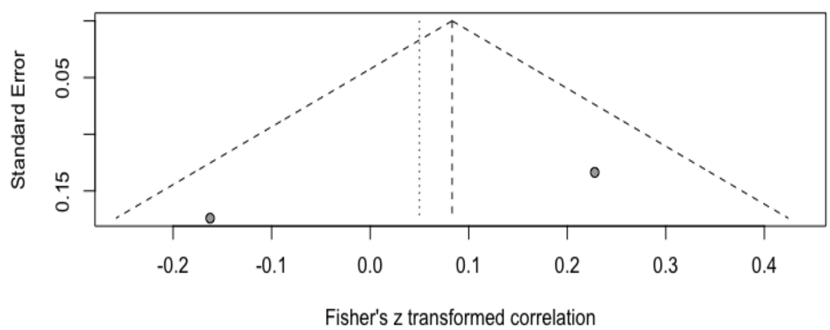


Figure 9.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of acute cognitive stress without SECPT.



A final meta-analysis pooling two effect sizes using the HDT task found a significant positive relationship between acute cognitive stress and HDT (r = 0.305 (0.112 – 0.477), p = 0.002), with between study heterogeneity estimated to be low as evidence by a non-significant Q test (Q = 0.26, p = 0.609), $T^2 = 0.001$ and $I^2 = 0\%$ (see Appendix B).

Chronic self-reported stress

Eleven effect sizes were pooled, and composite scores were created for three studies by averaging effect sizes from five (Schultchen et al., 2019), two (Tabor et al., 2019) and nine (Schenk et al., 2020) subscales. A significant negative relationship between cardiac interoceptive accuracy and self-reported stress of r = -0.107 (-0.197; -0.015; p = 0.02) was observed, which indicates that higher levels of self-reported stress appeared to be related to lower cardiac interoceptive accuracy scores. Individual effect sizes from each study are summarised in Figure 10. No significant outliers were identified as demonstrated by the forest plot, where all individual effect sizes overlapped with the 95% CI (Figure 10). A non-significant Egger's test (t = 2.056, p = 0.07) and a slight symmetry demonstrated in the funnel plot are suggestive of no publication bias (Figure 11). Heterogeneity analyses showed a T^2 value of 0.009 and a Q value of 17.87 (p = 0.06), which is consistent with a I^2 value of 44 % indicating moderate heterogeneity. Influence analyses using the leave-one-out method indicated effect sizes ranging from -0.14 to -0.07, one of which was non-significant indicating that individual studies substantially influenced the pooled effect size.

A sub-analysis pooling the effect sizes of two studies that used the HDT task reported no significant relationship between cardiac interoceptive accuracy and self-reported stress, although a trend towards a positive relationship was apparent (r = 0.14 (-0.014 – 0.288), p = 0.075; Appendix B). The between study heterogeneity was estimated to be low considering a non-significant Q value (Q = 0.03, p = 0.855), $T^2 < 0.001$ and $I^2 = 0\%$ (see Appendix B).

Figure 10.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of chronic self-reported stress.

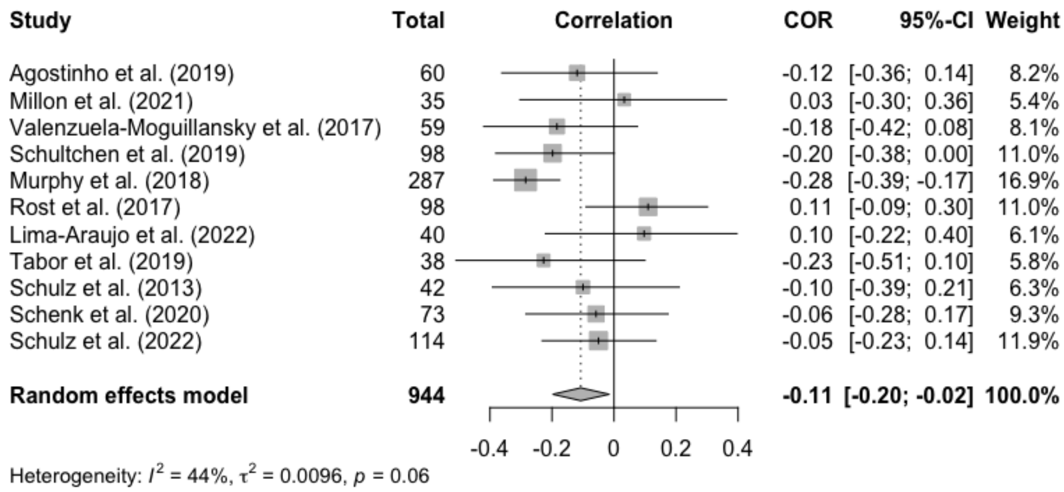
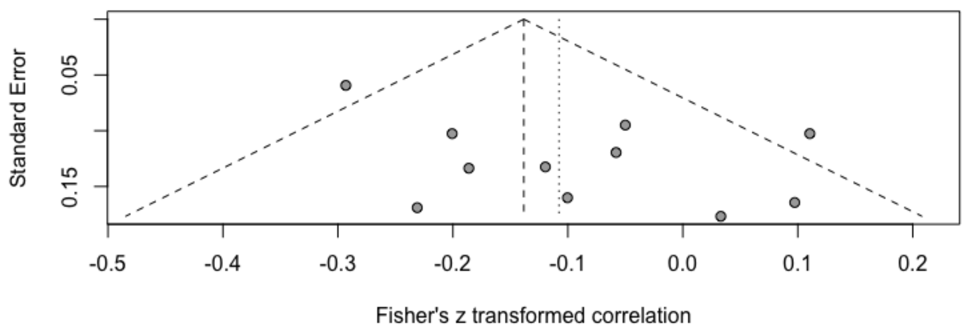


Figure 11.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of chronic self-reported stress.



Physiological stress response

A total of nine effect sizes were pooled, including four composite scores obtained from averaging two effect sizes from different measures taken in the same study (Herbert et al., 2010; Rost et al., 2017; Schultchen et al., 2019; Williams et al., 2021). As the pooled effect sizes included HRV measures, where higher scores are indicative of lower stress, as well as cortisol measures where higher scores indicate higher stress, the direction of the effect of all HRV measures was adjusted by changing the direction of the relationship for the effect sizes to be comparable. A significant negative relationship was observed between cardiac interoceptive accuracy and physiological stress response $r = -0.13$ (-0.239; -0.019; $p = 0.022$), indicating that higher HRV and lower cortisol scores are related to increased cardiac interoceptive accuracy. Individual effect sizes are shown in Figure 12. No significant outliers were identified as can be observed by the forest plot, where all studies overlap with the 95% CI of the pooled effect size (Figure 12). There was an insufficient number of studies to perform Eggers' test, but the slight funnel plot asymmetry might be indicative of publication bias (Figure 13). The T^2 value of 0.009, the non-significant Q test ($Q = 6.96$, $p = 0.541$) and low I^2 value of 0% are all suggestive of low heterogeneity. The influence analysis using the leave-one-out method demonstrated a range of significant effect sizes ranging from -0.15 to -0.11, indicating that the pooled effect size was not influenced by individual studies.

Two subsequent meta-analyses were performed to analyse individual relationships between HRV, cortisol and cardiac interoceptive accuracy. The pooled effect size of the five studies that used HRV measures was non-significant ($r = -0.128$ (-0.296 – 0.048); $p = 0.154$), with heterogeneity estimated as low given a non-significant Q value of 5 ($p = 0.287$), a T^2 value of 0.018 and $I^2 = 20\%$. The pooled effect size from the four studies using a cortisol measure showed a non-significant negative trend ($r = -0.137$ (-0.273 – 0.004); $p = 0.056$), with heterogeneity estimated to be low as evidenced by a non-significant Q value of 1.92 ($p = 0.59$), $T^2 = 0.003$ and $I^2 = 0\%$. A subgroup comparison between cortisol and HRV measures showed no significant between group difference ($Q = 0.007$, $p = 0.933$).

A meta-analysis conducted by pooling two effect sizes from studies that employed the HDT measure revealed a non-significant result ($r = -0.09$ (-0.243 – 0.066); $p = 0.257$), and low between study heterogeneity indicated by a non-significant Q value of 0.12 ($p = 0.726$), $T^2 < 0.001$ and $I^2 = 0\%$ (see Appendix B).

Figure 12.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of physiological stress response.

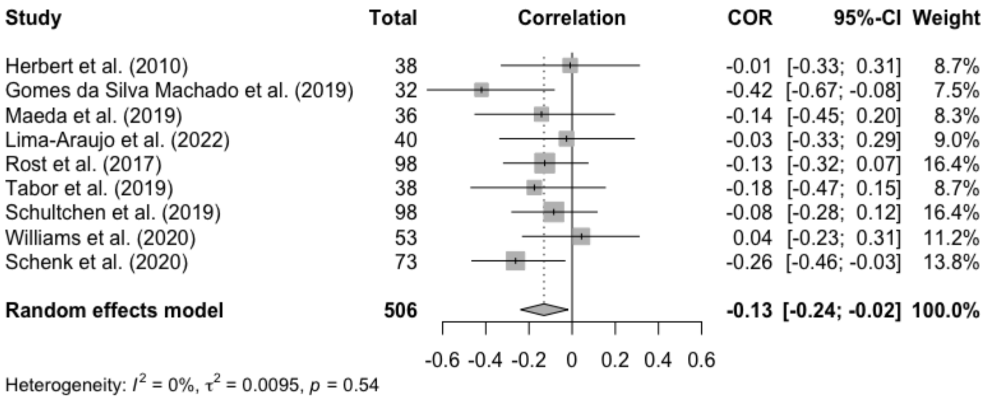
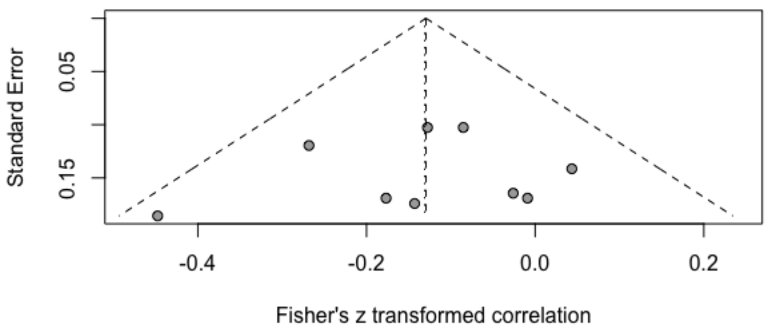


Figure 13.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of physiological stress response.



Sex differences

A final meta-analysis was conducted to explore sex differences in the relationship between cardiac interoceptive accuracy as measured by the HCT task and stress. Although a pattern was observed across different stress measures where females appeared to show a negative relationship between cardiac interoceptive accuracy and stress, while males exhibited a positive relationship, this difference was non-significant overall (p = 0.264). Characteristics of the included studies and detailed results are summarised in Appendix D.

Discussion

The aim of this meta-analysis was to investigate the relationship between cardiac interoceptive accuracy and stress, focusing on how performance on the HCT task relates to four different domains of the stress response. Although the results appear to suggest a relationship between cardiac interoceptive accuracy and stress, this effect should be interpreted with caution due to the large heterogeneity, indications of publication bias and influence of individual studies on the pooled effect sizes for several comparisons.

First, a moderate positive relationship was observed between cardiac interoceptive accuracy and acute physical stress, as measured by comparing cardiac interoceptive accuracy scores at baseline and after engaging in physical activity, suggesting that cardiac interoceptive accuracy appears to improve after engaging in a physical stressor task. Physical stressors are reported to trigger the stress response through an initial activation of the SAM system which provides rapid physiological adaptation, followed by a secondary HPA axis activation which supports an amplified and prolonged response (Godoy et al., 2018). Thus, physical stressors result in a fast and prolonged activation of the SNS, which stimulates and amplifies cardiac signals. This could improve signal detection during the HCT via an increase in stimulus strength. However, it is also possible that perceptual mechanisms are at play. It has been suggested that acute stress alters the perception of internal body states, which could be mediated by attentional processes (Schulz & Vögele, 2015). It is possible that acute physical stress leads to the perception of elevated heart rate, which could in turn generate more physical sensations, therefore increasing the strength of the heart rate signal, which would in turn improve cardiac interoceptive accuracy. Increased attention to elevated cardiac sensations could also lead to heightened stress, therefore generating a positive feedback loop that maintains elevated levels of both stress and cardiac interoceptive accuracy (Schulz & Vögele, 2015).

On the other hand, no significant relationship was observed between acute cognitive stress and cardiac interoceptive accuracy, consistent with evidence supporting the role of signal strength in the relationship between interoception and stress (Schulz & Vögele, 2015). Moderate heterogeneity was observed in the meta-analysis employing the acute cognitive stress tasks, which could be due to differences in the measures included, as one study employed a task that involved socio-evaluative aspects (TSST), one study included a task based on a time restriction paradigm (CRTT), and three studies included a combined physical stressor and socio-evaluative task (SECPT). Evidence suggests that acute cognitive stressors differ in the stress response they elicit based on their design, with those tasks including a social evaluative component eliciting HPA axis activation, while stressors that have no social evaluative component are thought to be limited to SAM system activation (Schulz et al., 2020). Therefore, it could be hypothesised that the stressors included in the meta-analysis activate different domains of the stress response, with the TSST and SECPT activating both the HPA axis and SAM systems, while the CRTT might only be triggering SAM system activation. Schulz et al. (2020) proposed that SAM system activation might have a dual impact on interoceptive accuracy (1) improving interoceptive accuracy in early stages by facilitating the generation of physical signals through peripheral sympathetic nervous system activation and, (2) decreasing accuracy at later stages through the activation of the central noradrenergic system, which is believed to increase alertness while decreasing the capacity for focused or selective attention, which could interfere with performance in the HCT task. This theory is supported by evidence suggesting that acute stress is related to impairments in higher order cognitive functions such as attention (Sänger et al., 2014) and working memory (Qin et al., 2009), in favour of facilitating adaptive fight-or-flight responses by relocating cognitive resources. Additionally, a study comparing the effects of physical and cognitive stressors on heart rate reported significant differences across different stressors and concluded that these were not comparable, as exercise appeared to have the biggest impact on heart rate, as evidenced by a rapid and prolonged elevation of participant pulse, while cognitive stressors appeared to initially elevate heart rate to a lesser degree followed by a steady decrease (Sharpley & Gordon, 1999). This is suggestive that physical exercise might amplify cardiac signals further than cognitive stressors therefore facilitating perception (Schulz & Vögele, 2015). Additionally, it could be hypothesised that higher order cognitive functions needed for the successful completion of the HCT task might be compromised by both acute physical and cognitive stress tasks. However, as stimulus strength is more salient in physical stress conditions due to the simultaneous SAM system and HPA axis activation, which leads to rapid and sustained cardiac reactivity, this may improve HCT performance via an increase in stimulus strength. In contrast, less change in signal strength and competing cognitive resources might result in absent (as observed here) or opposing effects for HCT performance after a cognitive stressor. The extent to which cognitive tasks create stress demands, as well as individual susceptibility to such stressors, may therefore contribute towards mixed findings. Despite the consistency of these conclusions with the broader literature, it should be noted that few effect sizes were pooled for this analysis, which was further reduced to two studies when studies employing a combined physical and cognitive acute stressor (SECPT) were removed (though including and removing the SECPT did not alter the pattern of significance observed). Combined with the moderate heterogeneity, influence from single studies, and potential publication bias observed, these results should thus be considered preliminary.

Regarding the relationship between interoceptive accuracy and self-reported chronic stress, a small negative effect was observed, indicating that low interoceptive accuracy might be associated with increased chronic stress. However, it is important to highlight that one study significantly influenced the pooled effect size, suggesting that the observed effect could be inflated and should be interpreted with caution. Nevertheless, the observed pattern of results is supported by previous studies which consistently report a negative relationship between interoceptive accuracy and chronic long term stress (Schulz et al., 2020). A potential explanation for this relationship could be the role of the insular cortex, a key brain structure for the integration of interoceptive, exteroceptive, vestibular, premotor and homeostatic activity (Schulz & Vögele, 2015) which is involved in the detection of stimulus saliency (Menon & Uddin, 2010). In other words, a stimulus could become more salient if relevant for the maintenance of homeostatic balance. For example, the smell of food would be more salient for an individual with low blood glucose levels compared to an individual with normal blood glucose levels (Koeppel et al., 2020). In the case of stress, it could be hypothesised that individuals with better cardiac interoceptive accuracy may be better able to identify stressful situations enabling them to maintain homeostasis by regulating their heart rate and/or reducing long term exposure to stressors (Koeppel et al., 2020), consistent with evidence that cardiac interoceptive accuracy relates to emotion regulation (Brewer et al., 2021). In contrast, those with poor cardiac interoceptive accuracy may have increased exposure to chronic stress due to inaccurate perception of stress signals, resulting in poorer avoidance of stressors. Additionally, there is extensive evidence suggesting that chronic stress causes both HPA axis and SAM system dysfunction (Pechtel & Pizzagalli, 2011; Schulz et al., 2020). It has been proposed that this dysfunction could disrupt interoceptive accuracy by impacting both signal amplitude and perception, feeding into a positive feedback loop where normal sensations are perceived as symptoms, therefore triggering stress and further activating the stress response (Schulz et al., 2020). Both these mechanisms could be acting jointly, as interoceptive disruption related to chronic stress induced hypo-reactivity of the HPA axis and SAM system could be perpetuating chronic stress by prolonging exposure to stressors, whilst hyperreactivity of those stress systems could have a worsening effect on interoceptive accuracy by decreasing signal strength.

Finally, results regarding the relationship between the physiological stress response and cardiac interoceptive accuracy also indicated a small negative relationship, representing a negative relationship between cortisol and cardiac interoceptive accuracy, and a positive relationship between HRV and cardiac interoceptive accuracy, as scores were adjusted. However, sub-analyses separating the two physiological measures produced no significant results, although a negative trend was observed between cardiac interoceptive accuracy and cortisol. It is important to interpret these results with caution due to the large heterogeneity observed among the studies, which could be explained by the studies measuring different aspects of the stress response including the HPA axis, SAM system and ANS activation, as well as the employment of different methods of measurement such as various HRV calculations and different methods for collecting cortisol. Nevertheless, the trend results regarding cortisol appear to be consistent with evidence supporting a negative relationship between chronic stress and interoceptive accuracy (Schulz et al., 2020). Chronic stress is associated with a cortisol dysfunction, that might result in a blunted cortisol response to stressors (Hannibal & Bishop, 2014). Cortisol is a key anti-inflammatory response that follows form the initial inflammation caused by the SAM system activation through the release of Epinephrine (E) and Norepinephrine (NE), which is essential for maintaining homeostatic balance and regulating the stress response (Tsigos & Chrousos, 2002). Although cortisol shows an elevation after acute stress, exposure to prolonged and chronic stress is associated with a reduced cortisol response which is adaptive as it facilitates regulation of the stress response and homeostatic balance (Guilliams & Edwards, 2010). Reduced cortisol levels appear to be associated with an increased sympathetic activation through the reduced inhibition of the SAM system response to stressors, therefore resulting in a heightened stress response (Fries et al., 2005). As the SAM system stimulates sympathetic responses to stress such as increased heart rate and blood pressure, it could be hypothesised that reduced cortisol would enhance interoceptive signal strength through reduced inhibition of the SAM system, thus facilitating better perception of heartbeats.

In terms of HRV, a positive relationship between interoceptive accuracy and HRV has been reported by previous research consistent with our results (Lischke et al., 2021). A proposed mechanism for this association relates to the role of the prefrontal and limbic brain regions for both cardiac interoceptive accuracy and parasympathetic activity (Lischke et al., 2021). It is proposed that the mechanisms mediating the relationship between interoceptive accuracy and HRV are higher order executive control processes such as selective, focused and switching attention, which are associated with prefrontal and limbic system activity, as well as HRV (Lischke et al., 2021). In summary, although a relationship was observed between the physiological stress response and cardiac interoceptive accuracy, due to the heterogeneity of the measures included and the lack of relationships when examining measures separately, the results must be interpreted with caution.

Limitations

When interpreting the results of this meta-analysis, it is important to consider the limitations. First, the relationship between cardiac interoceptive accuracy and stress was only explored with the HCT task, as there were an insufficient number of studies employing the HDT task, and no studies employing other tasks of interoceptive accuracy such as gastric or respiratory. Problematically, due to the large heterogeneity and variance between these tasks (Ceunen et al., 2013; Garfinkel, Manassei, et al., 2016; van Dyck et al., 2016), the effects observed between cardiac interoceptive accuracy and stress are not generalisable to other interoceptive domains. There are also additional methodological limitations regarding the measurement of cardiac interoceptive accuracy as interoceptive accuracy appears to improve after exposure to acute physical stress using the HCT but not the HDT task, with the opposite pattern observed for acute cognitive stress (Schulz et al., 2020). The mechanism underlying these contradictory findings remains unclear, thus affecting the generalisability of the results observed between cardiac interoceptive accuracy and stress, as there was an insufficient number of studies to perform reliable meta-analyses with studies employing the HDT task. Given the main difference between both cardiac interoceptive accuracy tasks is the allocation of attentional resources to only interoceptive (HCT), or both interoceptive and exteroceptive signals (HDT), it is possible that attentional processes could be mediating the relationship between cardiac interoceptive accuracy and stress. However, as the validity of the HCT task for measuring cardiac interoceptive accuracy has been consistently questioned with concerns regarding participants' use of estimation strategies (Desmedt et al., 2023), as well as an absence of standard operating procedures and guidelines in studies employing the HCT task (Corneille et al., 2020), results should be treated with caution. Indeed, as the current meta-analysis was only able to include studies employing the HCT task due to lack of responses from authors for data requests, no definitive conclusions can be drawn about the relationship between cardiac interoceptive accuracy and stress more broadly. Nevertheless, although there was an insufficient number of studies employing the HDT task to reliably pool effect sizes, the preliminary results may suggest discrepancies between the HCT and HDT tasks and how they relate to different stress domains. Finally, another limitation of the HCT task is the inability to manipulate and control signal strength effectively, therefore leading to cofounding effects due to signal strength not remaining constant across individuals (Desmedt et al., 2023). This is particularly problematic for investigating the relationship between interoceptive accuracy and stress, as stress appears to enhance signal strength. Future research could employ measures of respiratory or gastric interoceptive accuracy, which appear better able to control signal strength, thus enabling us to examine whether stress impacts interoception by way of increasing perception, as well as signal strength (Desmedt et al., 2023).

Second, there was an insufficient number of studies to perform meta-analyses exploring the presence of sex differences in the relationship between cardiac interoceptive accuracy and stress. This is important because of the evidence supporting the role of sex differences in the experience of psychological stress, as females appear to be more likely to report higher levels of stress and more physical and emotional symptoms of stress compared to their male counterparts (American Psychological Association, 2012). Biological differences in the stress response have also been widely reported, with males exhibiting greater HPA axis activation and higher cortisol levels, while female sex hormones appear to be associated with an attenuated HPA axis response (Verma et al., 2011). Additionally, the evidence regarding sex differences in interoceptive accuracy is mixed, as males appear to be more accurate than females when interoceptive accuracy is measured with the cardiac HCT and HDT tasks and respiratory resistive load tasks, but not when measured with respiratory elastic load tasks or tests of gastric interoceptive accuracy (Prentice & Murphy, 2022). Considering the evidence regarding the role of sex differences in both cardiac interoceptive accuracy and stress, sex differences could be an important factor influencing the observed effects.

Third, the small number of studies included in the meta-analysis also limits conclusions. The heterogeneity of the samples was large, and we also observed evidence of publication bias and influential single studies. Although authors were contacted to request data, many authors did not respond, with some authors no longer having access to the data. Finally, whilst we classified measures into four categories to enable a summary of results, studies employing tasks of acute cognitive stress activate different domains of the stress response and included various stressors such as social evaluation and combined physical and acute stressors. Similarly, studies measuring the physiological stress response also appear to elicit different cortical, limbic, and sympathetic activation, but the number of studies identified was too small to reliably explore these effects separately. Therefore, in the absence of larger number of studies to enable separation of tasks, it is difficult to derive definitive conclusions.

A final limitation of the current meta-analysis refers to the stringent search strategy, as no terms were included to directly search for studies employing measures of other domains of interoceptive accuracy such as respiratory or gastric. Equally, the search terms included for stress were also limited, as no terms were included to search for studies employing exercise or cognitive tasks as a stressor, as well as measures of cortisol or HRV. Although the search strategy was deliberately designed to limit the number of studies identified to relevant studies, less stringent search terms could provide more clarity on the broader relationship between interoceptive accuracy and stress that is not limited to the cardiac domain.

Clinical implications

There are various clinical implications derived from the effects observed between cardiac interoceptive accuracy and different stress domains. First, there is evidence to suggest that stress shares pathogenic mechanisms with other mental health disorders such as depression, Post Traumatic Stress Disorder (PTSD), and anxiety disorders (Godoy et al., 2018). For example, shared mechanisms include alterations in HPA axis activation or the increased risk of developing psychopathology after experiencing early life stress (Godoy et al., 2018). Additionally, atypical interoceptive accuracy is also associated to the development of physical and mental health symptoms, and is hypothesised to interact with stress through mechanisms involving the amplification of signals leading to the perception of normal sensations as pathological (Schulz et al., 2020). This can in turn generate a positive feedback loop, as the perception of physical symptoms can increase stress (Schulz et al., 2020).

Clarifying the underlying mechanisms between interoceptive accuracy and stress could promote the development and clinical application of transdiagnostic interventions for physical and mental health conditions. For example, an existing non-invasive intervention reported to increase interoceptive accuracy involves Heartbeat Perception Training (HBPT) through the visual feedback of heartbeats (Schulz et al., 2020). HBPT could be easily administered through mobile phone applications and could be facilitated alongside other therapeutic approaches that target physical symptom reduction such as Cognitive Behavioural Therapy (CBT) or Exposure and Response Prevention (ERP) in the treatment of various physical and mental health conditions. Hence, future research could focus on creating transdiagnostic interventions that directly target the interplay between interoceptive accuracy and the stress response.

Conclusion

Taken together, the results of this meta-analysis tentatively support the presence of a relationship between HCT performance and stress, with the observed effect being positive for acute physical stress and negative in the case of chronic stress and physiological stress response. However, given the small number of studies, the large heterogeneity observed, the presence of publication bias, influential single studies, and limitations regarding the generalisability of effects to other interoceptive accuracy tasks, these results should be treated with caution. Questions also remain regarding the role of sex differences in this relationship. Therefore, future research should focus on the relationship between interoceptive accuracy and stress using contemporary measures of cardiac interoceptive accuracy, as well as exploring the role of sex differences.

Chapter 2. The relationship between interoception and stress:

An experience sampling study

Abstract

Interoception, the processing of one's own body signals, has been related to numerous mental and physical health conditions including stress. However, large discrepancies in the definitions and theories of interoceptive processes have led to important methodological limitations. This has resulted in limitations in our understanding of the mechanisms that mediate the relationship between interoception and mental health, particularly stress. As such, the aim of the present study was to investigate the relationship between interoception and stress using an improved methodological framework for assessing interoception, as well as a multi-measure approach for assessing stress. We predicted that (1) trait and state stress would be negatively associated with objective interoceptive accuracy; (2) trait and state stress would be positively associated with trait self-reported interoceptive attention; (3) trait and state stress would be negatively associated with trait self-reported interoceptive accuracy; and (4) state interoceptive attention would be positively related to trait, state, and physiological stress. Correlational analyses of trait-based measures of interoception and stress demonstrated different relationships between trait interoception and stress. Specifically, trait interoceptive attention was positively associated with self-reported and physiological stress, while trait interoceptive accuracy was only negatively associated with self-reported stress but not physiological stress. Multi-level models of the experience sampling data (state measures) showed positive relationships between state measures of interoceptive attention and state stress. No relationship was found between the objective measure of interoceptive accuracy and trait or state measures of stress. Clinical implications and limitations of the present study are considered.

Introduction

Stress is a multidimensional construct that encompasses different processes including exposure to stressors, as well as the psychological and physiological responses to such stressors (Harkness et al., 2020; see Chapter 1 for a detailed description of the stress response). Research about stress is prominent due to its clinical relevance, as stress appears related to the development of numerous physical and mental health conditions (Harkness et al., 2020). For example, early life stress is associated with an increased risk of developing chronic physical conditions (Nelson et al., 2020) and mental health disorders in adulthood (Carr et al., 2013). Additionally, chronic stress is also associated with life-threatening diseases such as cardiovascular disease, insulin insensitivity, cancer and inflammation (Rohleder, 2019). Problematically, the term stress broadly encompasses stressors, acute stress, chronic stress and the stress response, which are measured with a range of tools including self-report questionnaires, paradigms eliciting acute stress in laboratory settings, physiological measures and naturalistic ecological measures (Crosswell & Lockwood, 2020). Difficulties defining and measuring stress have hampered understanding of the mechanisms underpinning the relationship between stress and pathology.

Interoception, the processing of one's own internal bodily signals and physiological states (Craig, 2003), is thought to play a mediating role in the relationship between stress and pathology, where the perception of bodily signals as threatening increases stress which in turn generates stress-related physical symptoms (Schulz & Vögele, 2015). However, the evidence investigating the relationship between interoception and stress is mixed (as discussed in Chapter 1). In terms of cardiac interoceptive accuracy (performance on objective tests), some studies demonstrate improvements in interoceptive accuracy after an acute stressor when interoceptive accuracy is measured with the Heartbeat Counting Task (HCT), but not the Heartbeat Detection Task (HDT; described below; see Chapter 1; Schulz et al., 2013), while others suggest that this relationship may vary by sex (Fairclough & Goodwin, 2007). On the other hand, evidence regarding the relationship between self-report measures of stress and cardiac interoceptive accuracy is scarce, with most studies suggesting a weak negative relationship (e.g., Schultchen et al., 2019; see Chapter 1).

A possible explanation for the mixed results in research between interoception and stress relates to the limitations of existing tools for measuring interoception (Desmedt et al., 2023; as discussed in Chapter 1). With regards to accuracy, the most frequently investigated domain, cardiac interoceptive accuracy, is typically assessed with the HCT, where participants are instructed to count their heartbeats across different time intervals (Schandry, 1981), or the HDT where participants are asked to determine whether a series of visual or auditory stimuli are synchronous with their heartbeats (Whitehead et al., 1977). Both tasks have been criticised due to producing false positives resulting from the cofounding effects of prior knowledge about heartrate, and false negatives due to individual differences in delays for perceiving heartbeats respectively (Brener & Ring, 2016; Desmedt et al., 2023). A recently developed task of cardiac interoceptive accuracy, the Phase Adjustment Task (PAT), appears to overcome these limitations, therefore providing a promising non-invasive measure (Desmedt et al., 2023; Plans et al., 2021). However, although previous work using this measure suggests no relationship between self-reported stress and cardiac interoceptive accuracy (Plans et al., 2021), it remains unknown whether a relationship would be found with other measures of stress (e.g., physiological measures).

Second, the most frequently used questionnaire measures of self-reported interoception appear to be weakly correlated, suggesting that they do not measure a common underlying construct (Desmedt et al., 2022). A possible explanation relates to these questionnaires being developed to measure ‘interoceptive sensibility’, an umbrella term encompassing many interoceptive beliefs (Desmedt et al., 2022). Hence, new measures have attempted to improve the definition of constructs by assessing beliefs associated with specific interoceptive dimensions such as accuracy or attention (Gabriele et al., 2022; Murphy et al., 2020). Importantly, these measures appear to be unrelated, supporting that accuracy and attention are two separate dimensions of interoception (Gabriele et al., 2022; Suksasilp & Garfinkel, 2022). However, even with separation of these dimensions results are somewhat mixed regarding the relationship between self-reported interoception and stress. Evidence suggests a relationship between self-reported beliefs about one's interoceptive accuracy and self-reported stress, whereby lower self-reported stress is associated with higher self-reported interoceptive accuracy, but not with self-reported interoceptive attention (Benau, 2023). In contrast, evidence suggests that those with stress-related disorders appear to report higher attention to interoceptive signals compared to healthy controls (Bogaerts et al., 2022). Again, it remains unclear whether this is due to differences in the measurement of stress across studies.

An alternative possibility is that the relationship between interoception and stress is state-dependent. Indeed, evidence suggests that interoceptive accuracy involves both state and trait factors (Plans et al., 2021) and the same is true for interoceptive attention (Poerio et al., 2024) and stress (Thorn et al., 2009). Importantly, for measures of interoceptive attention, state and trait measures are only weakly correlated, highlighting the need to use both ecologically valid in the moment measures alongside retrospective measures to fully understand relationships (Murphy, 2024).

Given the numerous methodological limitations in the assessment of both interoception and stress, there is currently insufficient evidence to establish a relationship between different domains of interoception and stress. As such, the aim of this study was to assess all facets of the 2x2 factorial model of interoception (Murphy, Catmur, et al., 2019) using contemporary measures that overcome the limitations of existing tools and examine their relationship with multiple measures of stress. Hence, we assessed objective interoceptive accuracy, trait self-reported interoceptive accuracy, trait self-reported interoceptive attention and state self-reported interoceptive attention. For stress, we used measures of self-reported stress, alongside physiological measures, and state self-reported measures. Based on the current evidence, we predicted that (1) trait and state stress would be negatively associated with objective interoceptive accuracy (Schaan et al., 2019; Schultchen et al., 2019); (2) trait and state stress would be positively associated with trait self-reported interoceptive attention (Bogaerts et al., 2022), (3) trait and state stress would be negatively associated with trait self-reported interoceptive accuracy (Benau, 2023). We also predicted that (4) state interoceptive attention would be positively related to trait, state, and physiological stress as higher attention to body signals is associated with increased stress symptomatology (Hayward et al., 2000). Finally, exploratory analyses were used to assess the role of sex differences, with preliminary predictions that women would score lower on interoceptive accuracy and higher on state attention than men (Murphy, Viding, et al., 2019; Prentice & Murphy, 2022), which would be positively related to trait and state stress (Fairclough & Goodwin, 2007).

Method

The Royal Holloway University of London (RHUL) Research and Ethics Committee approved the study in February 2021, with subsequent amendments submitted and approved as required (refer to Appendices E to G to see the participant information sheet, consent form and debrief documents).

Participants

The target sample size was calculated using a power analysis. As effect sizes were unknown for experience sampling measures, power calculations using G*Power (Faul et al.,

2007) for a medium effect size (d = 0.5) suggested that a sample size of 118, would provide >80% power to detect significant effects. A medium effect size was selected as it is considered to be a reasonable estimate to detect useful effects in psychological research (Brysbaert, 2019).

The inclusion criteria for this study comprised working age individuals (18-65) without visual or hearing impairments. Participants were recruited via opportunity sampling using adverts placed on the RHUL undergraduate student pool management system, posters placed across campus, and through emailing of various undergraduate, postgraduate, and doctoral mailing lists. Participants received compensation in the form of credits for psychology undergraduate students and a £15 Amazon voucher for participants who were ineligible for credits. Participants that scored over the cut-off for moderate scores on the mental health questionnaires were also provided with a wellbeing support sheet in accordance with the ethical approval (see Appendix H).

A total of 132 participants were recruited but 15 participants missed the first testing session, therefore leading to a final sample of 117 participants (66 females). The sample included missing data from participants who completed the study but had unavailable data from tasks using mobile phone applications due to technical difficulties. Sample characteristics divided by the experience sampling condition (ESM; described below; interoceptive, auditory) are summarised in Table 6.

Table 6.

Descriptive characteristics of participants included in the study, divided by ESM condition.

	Male (%)	Female (%)	Age (SD)	Age range	Mental health (%)	Physical health (%)
Interoceptive group	21 (41%)	30 (59%)	23.31 (9.021)	18-63	7 (14%)	4 (8%)
Auditory group	24 (49%)	25 (51%)	22.99 (7.073)	18-55	10 (20%)	9 (18%)

Measures

Attention checks were placed within each survey to detect inattentive responders. Attention checks are reported to increase the construct validity of scales and detect a higher number of inattentive responders when multiple checks are employed (Shamon & Berning, 2019). Thus, one attention check was included per survey in the form of directed queries, for example 'Most of the time my attention is focused on completing this study. To prove this is true, select 'strongly agree''.

Interoception measures:

1. *Interoceptive Accuracy Scale (IAS; Murphy et al., 2020)*

The 21-item IAS was employed as a measure of trait interoceptive accuracy. Items are rated in a 5-point scale from strongly disagree (1) to strongly agree (5). Across three different studies, the measure was found to have good to excellent internal consistency ($\alpha = 0.88$; $\alpha = 0.90$) and good test-retest reliability ($r = 0.754$; Murphy et al., 2020). In a later study it was reported that 84% of participants who completed the IAS correctly interpreted the measure of interoceptive accuracy (Gabriele et al., 2022). However, as this was not universal an interpretation item was included at the end of the questionnaire to verify understanding. Please see Appendix I to refer to the IAS questionnaire.

2. *Interoceptive Attention Scale (IATS; Gabriele et al., 2022)*

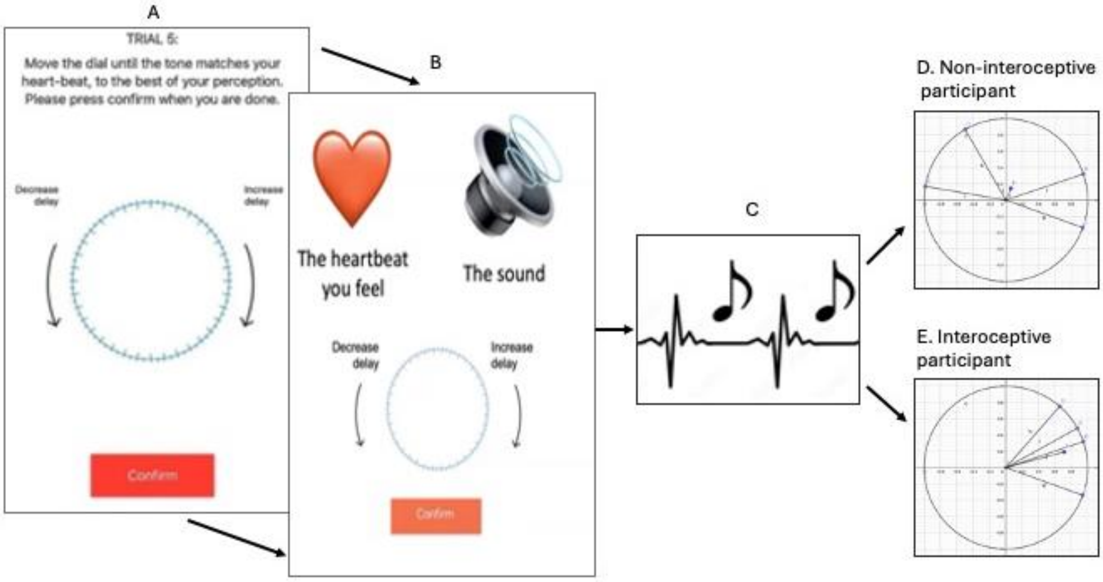
The IATS is a is a 21-item trait-based self-report measure of attention to internal signals with items rated in a 5-point scale from strongly disagree (1) to strongly agree (5). The IATS was developed to ensure that items matched the same physical sensations as the IAS (Gabriele et al., 2022). Although 79% of participants reported to interpret the IATS as a measure of interoceptive attention (Gabriele et al., 2022), like the IAS we included an interpretation item at the end of the questionnaire to confirm this (see Appendix J). The IATS is positively correlated with an existing self-report measure of interoceptive attention (r = 0.354, $p < 0.001$) and is not significantly correlated with the IAS ($r = -0.072$, $p = 0.077$), indicating good construct validity (Gabriele et al., 2022). Preliminary validation studies also suggest the IATS has good internal consistency ($\alpha = 0.9$) and comparable test-retest reliability to existing measures of interoceptive attention ($r = 0.7$; Gabriele et al., 2022). Please refer to Appendix J for the IATS questionnaire.

3. *Phase Adjustment Task (PAT; Plans et al., 2021)*

The PAT task uses a camera-driven photoplethysmogram sensor to detect participant heartbeat, which has been reported to be a valid measure of heart rate when participants are not in motion (Morelli et al., 2018). The PAT task has also been reported to have moderate consistency between two measurements taken a week apart (Plans et al., 2021). In the PAT, participants are presented with a series of tones that are triggered by the heartbeat, but out of phase. They are instructed to use a dial to advance or delay auditory tones until they perceive the tones to be synchronous with their heartbeat (See Figure 14; Plans et al., 2021).

Figure 14.

Example of PAT performance for interoceptive and non-interoceptive participants.



Note. (A) The screen display from one of the PAT trials, where participants are instructed to move the dial to advance or delay auditory tones; (B) A screenshot from the example demonstrating participants how to match their heartbeats to auditory tones using the dial; (C) A hypothetical example of participant performance matching tones and heartbeats with delays after their heartbeats; (D) A chart displaying the scores of a non-interoceptive participant who performed with inconsistent delays across trials, demonstrated by the dial positions being placed randomly on the circumference; (E) A chart displaying the scores of an interoceptive participant who performed with more consistent delays across trials demonstrated by the dial positions being placed closer together on the circumference.

As the starting phase is random across trials, the consistency of the participants response is taken as a measure of interoceptive accuracy and is calculated using the following equation (Figure 15):

Figure 15.

Equation for scoring the PAT.

$$Consistency\ (d, p) = \frac{1}{n} mod\left(\sum_{j=1}^{n} e^{i2\pi\frac{dj}{pj}}\right)$$

Note: d = selected delay, p = periodic function of the period, n = the number of considered angles.

The results range from 0 to 1, with 1 indicating absolute consistency over trials, while numbers close to 0 are indicative of dial positions on a standardised circumference being placed randomly, therefore suggesting lower interoceptive accuracy. Participants completed 2 practice trials followed by 20 trials.

To control for attention and motivation, participants also completed a structurally identical control task where they were instructed to use the dial to advance or delay two auditory tones until they were perceived to be synchronous with one another. To match heart rate and heart rate variability on an individual participant basis, one tone was triggered by the heartbeat and the other was out of sync (as per the PAT), but participants were not informed that any of the tones represented their heartbeat. As before, participants completed two practice trials and 20 task trials and results were scored in the same way as the PAT.

4. *Experience Sampling Method (ESM) of interoceptive attention*

The ESM is reported to have an adequate to good test-retest reliability, ranging from r = 0.45 to r = 0.80. ESM measures are reported to have good convergent and divergent validity as ESM results correlate with similar constructs to those measured using in the moment ratings, and they are also reported to differentiate between groups where differences are expected (Csikszentmihalyi, 2014). The ESM was completed via a smartphone application that prompted participants ten times daily to answer a question regarding their attention to either internal or auditory signals. The frequency and timing of the ESM prompts were tested using a pilot study, which determined that prompts ten times daily for six days provided a balance between the number of observations and participant retention. For those randomly assigned to report on their internal attention, participants were asked "*In the last 5 minutes, how much of the time were you paying attention to internal signals?*" and responded on a 5-point scale, from 'all of the last 5 minutes' (1) to 'none of the last 5 minutes' (5). Prior to responding, they were presented with examples on what would count as attention to internal signals and asked to confirm their understanding.

As it is recommended that research on interoceptive processing control for exteroceptive processing to determine whether the measure has good discriminant validity (Desmedt, Luminet, Walentynowicz, et al., 2023; Pang et al., 2019), half of the participants were randomly allocated to report on their attention to exteroceptive signals. Auditory signals were selected as a control as other senses are shown to overlap with the neural regions that process interoceptive signals (i.e. vision, olfaction and touch; Crucianelli & Ehrsson, 2023; Farb et al., 2013; Koeppel et al., 2020) and during waking hours vision is engaged most of the time. After confirming their understanding of what would count as attention to auditory signals, participants were asked '*In the last 5 minutes, how much of the time were you paying attention to auditory signals*?' and responded on the same 5-point Likert scale. Please refer to Appendix K to see ESM survey questions for both groups.

<u>Stress measures:</u>

Stress can be defined as relating to two distinct processes: exposure to external stressors, and stress responses which can be classified as physiological or psychological (Harkness et al., 2020). Due to the numerous limitations in the measurement of stress, we adopted a multi-measure approach to measure both exposure to, and response to life stressors. The aim of this approach was to determine the presence of a common stress construct(s).

5. *Depression Anxiety and Stress Scale (DASS-21) - Stress subscale (Lovibond & Lovibond, 1995)*

The DASS-21 was employed as a trait-based measure[3] of overall psychological distress, depression, anxiety, and stress. Items are rated on a 4-point scale from never (0) to almost always (3). The DASS-21 is reported to be a valid measure of overall psychological distress, as well as measuring three distinct subscales (Sinclair et al., 2012), and shows good reliability (α = 0.87 - 0.91), construct and structure validity (Bibi et al., 2020). The DASS-21 stress subscale has been reported to have acceptable internal consistency reliability in a large non-clinical US sample (α = 0.84; Sinclair et al., 2012). Although the Stress subscale of the longer version of the DASS (DASS-42) was reported to have an excellent internal consistency (α = 0.93) and test-retest reliability in a clinical sample (from r = 0.71 to r = 0.81), it might not effectively discriminate stress from negative affect (Brown et al., 1997). Nevertheless, other self-reported measures of stress are reported to have similar limitations (Harkness et al., 2020). Additionally, unlike other stress questionnaires, the DASS-21 does not include items related to physical sensations. Therefore, the DASS-21 stress subscale was used as a trait-based measure of stress over the last week to ensure the independence of measurement from the self-report measures of interoception which contain items about physical sensations. Please refer to Appendix L to see the DASS-21 questionnaire.

6. *Social Readjustment Rating Scale (SRRS; Holmes & Rahe, 1967)*

The SRRS is a 43 item self-report measure of major life events and stress over the last 12-months. Dichotomous yes/no answers are rated using a 100-point score. The SRRS is reported to have good stability and reliability for non-clinical samples (r range = 0.83 - 0.59;

[3] Note that the DASS-21 measures emotional states over the last 2 weeks. As such, it is not a trait-based measure. The term 'trait' is used solely to distinguish this measure from the state momentary measures of stress used in the present study.

Gerst et al., 1978). Although some studies reported poor validity for the SRRS (Bieliauskas & Webb, 1974), a systematic evaluation supported the use of the SRRS for predicting stress-related outcomes when assessing stressors over the last 12-month period (r = 0.44; Scully et al., 2000). The SRRS was employed as a measure of long-term exposure to stressors (Appendix M).

7. *ESM measure of stress.*

ESM has been reported to have a high construct validity for measuring subjective stress responses and has been found to effectively differentiate clinical and non-clinical populations (Vaessen et al., 2015). After reporting on attention to auditory or internal signals, the ESM prompted participants to answer two questions, '*how stressed have you felt in the last 5 minutes?*' (ESM item 5) and '*how stressful was the activity or event you were involved with in the last 5 minutes*?' (ESM item 6) using a 5-point scale from not at all (1) to extremely (5). The items were aimed to ecologically assess both stress responses (hereafter 'state perceived stress') and exposure to stressors (hereafter 'state stressors'), as recommended for the assessment daily stress (Wright et al., 2020). Please refer to Appendix K for all ESM items.

8. *Heart Rate Variability (HRV).*

HRV is a physiological marker of stress as low HRV increases vulnerability to stress, and its use as an objective measure of physiological stress response is supported when used alongside other self-reported measures, due to stress being a physiological and psychological process (Kim et al., 2018). HRV was calculated with the RHRV package in R (Rodriguez-Linares et al., 2022), using the heartbeats detected by photoplethysmograph during the 2-minute baseline heart rate recording prior to the control task. After extracting beat-to-beat intervals (RR), core time-domain methods were deployed to calculate time analysis statistics

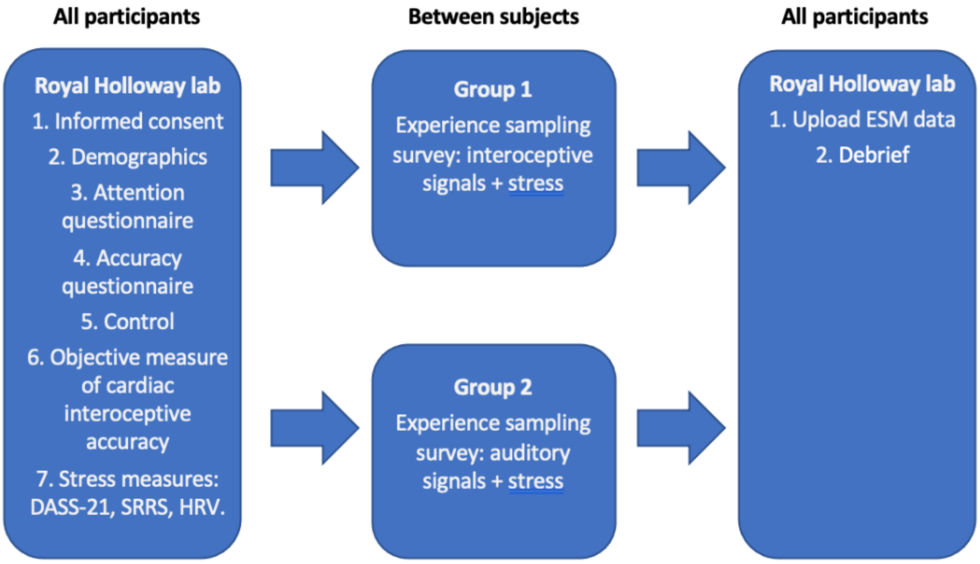
(HRV, SDNN, RMSSD and pNN50; Plans et al., 2021). Given the HRV variables RMSSD and SDNN appear to have the largest amount of evidence supporting their use as reliable metrics of stress (Immanuel et al., 2023), these HRV domains were included in analyses. As SDNN and RMSSD are measures of parasympathetic and vagus nerve activity, it is important to note that lower scores are related to increased stress (Gullett et al., 2023).

Procedure

First, a pilot study suggested less attrition when participants were initially tested in person. Thus, all participants were tested in person at the RHUL lab, or at University of London locations at Bedford Square and Senate House library from July 2023 to February 2024. Participants received the information sheet (see Appendix E) by email prior to attending the first testing session where informed consent was obtained (see Appendix F). At the beginning of the first testing session, they were provided with opportunities to ask questions or receive further information in accordance with the protocols approved by the ethics committee. Participants first completed the baseline demographic, stress, and self-report interoceptive accuracy and attention measures in Qualtrics, an experience management software for creating online surveys (Qualtrics, 2024). Then, participants completed the control task before completing the PAT task. Finally, participants were randomly allocated by the Qualtrics software to one of two ESM groups of either paying attention to auditory or internal signals and were supported to install the mobile phone application to complete the ESM at home for a period of 6 days. After completing the ESM, participants were invited back to the lab where the ESM data was downloaded. At this time, they were debriefed and offered the opportunity to ask any additional questions (Appendix G). The study design and procedure are summarised in Figure 16. Note that this study was part of a larger project and therefore some additional measures were administered but will be reported elsewhere. Please see Appendix M to refer to the full study design including all measures.

Figure 16.

Study design and procedure.



Data analysis:

Analysis strategy and data cleaning

For data cleaning purposes, data were excluded from analyses if (1) participants answered more than two attention checks incorrectly, (2) they incorrectly answered IAS and IATS interpretation questions, and (3) they completed less than 50% of the experience sampling surveys. As higher scores in the ESM questions regarding attention to internal or auditory stimuli reflected lower attention, the variables were recoded for ease of interpretation, so higher scores corresponded to higher attention.

All analyses were completed using SPSS version 28.0.1.1(14) and syntax (IBM, 2023). Assumptions of normality were checked using P-P plots, histograms, and Kolmogorov-Smirnov tests. Depending on whether the assumptions of parametric tests were met or violated, parametric tests or non-parametric equivalents were used accordingly. A Principal Components Analysis (PCA) was performed to explore the presence of shared construct(s) across the four stress measures (DASS-S, SRRS, RMSSD and SDNN) and extract common components. The assumption of equality of variance for performing a PCA was explored with the Bartlett's test of sphericity.

To test the first hypothesis that stress would be positively associated with objective cardiac interoceptive accuracy, correlation analyses were used to assess the relationship between the stress construct(s) and PAT performance. The same analysis was conducted with the control task, with the two correlations compared using r-to-z tests to test whether the relationship between PAT performance and stress construct(s) was greater than the control measure (Preacher, 2022). The relationship between state stress and objective cardiac interoceptive accuracy was assessed using a multi-level model with state stress as the dependent variable and interoceptive accuracy (PAT performance) as the fixed factor. To control for exteroceptive signals, the data was separately analysed for the internal and auditory ESM groups. The second hypothesis was assessed by examining correlations between the stress construct(s) and trait self-reported interoception (IAS and IATS), and multi-level models with state stress measures as dependent variables and trait self-reported interoception (IAS and IATS) as predictor variables, separately for the interoceptive and auditory groups. To test the third hypothesis and analyse whether there was a relationship between state interoceptive attention and stress measures (state and trait), multi-level models of the experience sampling data were performed due to data having a nested structure, with state attention and stress as level one variables (collected over different time points) and trait interoception and stress as level two variables (nested within individuals). Analyses were performed separately for the internal and auditory ESM groups. The between and within subject variance in the dependent variable was estimated using random intercepts for each individual. Finally, to answer the last hypothesis, exploratory analyses of sex differences were conducted by performing separate correlations for the trait interoception and stress variables, with correlations compared with subsequent r-to-z tests to establish any significant differences using an online calculator (Preacher, 2022). Multi-level models of state interoception and trait and state stress by sex were also completed by repeating the analyses separately for males and females in each group (interoception vs auditory).

Results

The Kolmogorov-Smirnoff test was non-significant for all variables excluding the control task ($D(68) = 0.221$, $p < 0.001$). Therefore, parametric tests were employed for all analyses that did not involve the control task, where non-parametric tests were employed instead[4]. The assumption of multicollinearity for multi-level modelling was met for both dependent variables (state stress and attention), as the variance inflation factor (VIF) values were below 10 for all interactions, indicating that predictor variables did not highly correlate with each other.

Principal Component Analysis (PCA)

A PCA was performed with the scores from two stress questionnaires (SRRS and DASS-S) and two HRV variables calculated from the control task (RMSSD and SDNN). An oblique rotation (direct oblimin) was employed as theory indicates that these measures could be related. Bartlett's test of sphericity indicated that correlations between variables were sufficiently large to conduct a PCA ($\chi^2 = 74.827$, $p < 0.001$). Two components had Eigenvalues over Kaiser's criterion of 1 and explained 76.226% of the variance. The scree plot was slightly ambiguous, but showed an inflexion that would justify separating two components. Therefore, two components were extracted. Table 7 shows the factor loadings after rotation. The factor clusters suggest that factor one might represent physiological stress (PCA Factor 1) while factor two might represent self-reported stress (PCA Factor 2). The

[4] Note that analyses were repeated using non-parametric tests for all comparisons that had little effect on the pattern of results obtained.

component correlation matrix demonstrated a small non-significant correlation between the extracted components (r = 0.136, p = 0.184)[5].

Table 7.

Pattern matrix showing factor loading after rotation.

	Component	
	1	2
RMSSD	.930	
SDNN	.897	
SRRS		.825
DASS-S		.824

Abbreviations: RMSSD Root mean square of successive differences between normal heartbeats, SDNN Standard deviation of all normal RR (NN) intervals during a 24-hour period, SRRS Social Readjustment Rating Scale, DASS-S Depression anxiety and stress scale – stress subscale. Coefficients below 0.4 were suppressed (Pituch & Stevens, 2016).

Relationship between stress measures

To compare the state stress measures, a multilevel fixed effects analysis was performed to examine the relationship between state perceived stress (ESM item 5, assessing momentary perceived stress) and state stressors (ESM item 6, assessing momentary perceived stressors). A significant relationship was observed for the interoceptive group (β = 0.706 (0.677 – 0.735), SE = 0.015, t(2368.340) = 47.739, p = 0) and auditory group (β = 0.659 (0.626 – 0.691), SE = 0.017, t(2388.085) = 39.666, p < 0.001), suggesting that higher perceived state stressors related to higher state stress levels as expected.

[5] Note that repeating the PCA with orthogonal rotation (Varimax) had little effect on the pattern of results obtained.

To examine the relationship between physiological measures of stress (PCA Factor 1; HRV) and state stress measures (ESM items 5 and 6), two fixed effect analyses were conducted with state stress measures as the dependant variable and physiological stress as a predictor. This demonstrated no relationship between state perceived stress (ESM item 5) and physiological stress (PCA Factor 1) for the interoceptive group (β = 0.007 (-0.149 – 0.162), SE = 0.077, t(41.06) = 0.085, p = 0.932), or auditory group (β = -0.02 (-0.156 – 0.115), SE = 0.067, t(41.37) = -0.302, p = 0.764). Similarly, a fixed effects analysis with state stressors (ESM item 6) as the dependent variable and physiological stress (PCA Factor 1) as the predictor demonstrated no significant relationship for the interoceptive group (β = -0.011 (-0.158 – 0.135), SE = 0.073, t(41.172) = -0.156, p = 0.877) or the auditory group (β = 0.016 (-0.098 – 0.131), SE = 0.057, t(41.733) = 0.289, p = 0.774).

Regarding the relationship between self-reported stress (PCA Factor 2) and state measures of stress (ESM items 5 and 6), a fixed effects analysis revealed no significant relationship between self-reported stress (PCA Factor 2) and state perceived stress (ESM item 5) for the interoceptive group (β = 0.122 (-0.073 – 0.316), SE = 0.096, t(41.201) = 1.265, p = 0.213), or the auditory group (β = 0.12 (-0.003 – 0.243), SE = 0.061, t(42.061) = 1.966, p = 0.056). Similarly, no relationship was observed between self-reported stress (PCA Factor 2) and state stressors (ESM item 6) for the interoceptive group (β = 0.005 (-0.181 – 0.194), SE = 0.092, t(41.288) = 0.057, p = 0.955) or the auditory group (β = 0.083 (-0.023 – 0.189), SE = 0.052, t(42.433) = 1.584, p = 0.121).

Relationship between measures of interoception

Regarding the interoceptive measures, a Pearson's correlation revealed no significant relationship between trait interoceptive accuracy (IAS) and trait interoceptive attention (IATS) as expected (r = 0.118, p = 0.137;see Table 3). Trait interoceptive accuracy (IAS) appeared to be negatively related to the objective measure of cardiac interoceptive accuracy

(PAT; r = -0.189, p = 0.041) and performance on the control task (r = -0.250, p = 0.029), indicating that higher beliefs about one's own interoceptive accuracy were correlated with worse performance on both tasks. R-to-z tests demonstrated that the sizes of those relationships were not significantly different (z = 0.408, p = 0.341). Trait interoceptive attention (IATS) was not significantly correlated with performance on the objective task of interoceptive accuracy (PAT) or the control task (see Table 8).

Table 8.

Correlation matrix.

Measure	1	2	3	4	5
1. Physiological stress	-				
2. Self-reported stress	.136	-			
3. IATS	-.206*	.315**	-		
4. IAS	-.029	-.220*	.118	-	
5. PAT	.125	.014	-.017	-.189*	-
6. Control	-.105	.143	-.105	-.250*	-.002

* Significant at 0.05 (1-tailed)

** Significant at 0.01 (1-tailed)

Abbreviations: IATS Interoceptive Attention Scale, IAS Interoceptive Accuracy Scale, PAT Phase Adjustment Task.

A fixed effect analysis with state attention (ESM item 3) as the dependant variable and trait interoceptive attention (IATS) as the predictor, revealed no significant relationship between trait interoceptive attention (IATS) and state attention (ESM item 3) for the interoceptive group (β = 0.017 (-0.007 – 0.041), SE = 0.012, t(41.932) = 1.456, p = 0.153).

However, a small significant relationship was observed between trait interoceptive attention (IATS) and state attention (ESM item 3) for the auditory group (β = 0.019 (0.002 – 0.037), SE = 0.009, t(39.223) = 2.245, p = 0.03), indicating that increased reported state attention (ESM item 3) to auditory signals was related to higher perceived attention to internal signals. No significant relationship was observed between trait interoceptive accuracy (IAS) and state attention (ESM item 3) for the interoceptive group (β = 0.004 (-0.027 – 0.036), SE = 0.016, t(40.996) = 0.285, p = 0.777), or the auditory group (β = -0.004 (-0.028 – 0.019), SE = 0.012, t(38.738) = -0.366, p = 0.717). Regarding objective interoceptive accuracy (PAT), no relationship was observed between performance on the objective measure of cardiac interoceptive accuracy (PAT) and state attention (ESM item 3) for the interoceptive group (β = -1.209 (-3.216 – 0.799), SE = 0.993, t(40.043) = -1.217, p = 0.231) or the auditory group (β = -0.927 (-2.008 – 0.155), SE = 0.536, t(40.985) = -1.731, p = 0.091). Finally, no relationship was observed between performance on the control task and state attention (ESM item 3) for the interoceptive group (β = 2.175 (-1.397 – 5.748), SE = 1.768, t(40.097) = 1.23, p = 0.226), or the auditory group (β = -0.131 (-1.729 – 1.467), SE = 0.792, t(43.12) = -0.166, p = 0.867).

Relationship between objective interoceptive accuracy and stress

Please see Table 3 to refer to the correlation matrix. First, no significant relationship was observed between objective interoceptive accuracy (PAT) and physiological stress (PCA Factor 1; r = 0.125, p = 0.124) or self-reported stress (PCA Factor 2; r = 0.014, p = 0.448). Likewise, no significant relationship was observed between performance on the control task and physiological (PCA Factor 1; r = -0.105, p = 0.153) or self-reported stress (PCA Factor 2; r = 0.143, p = 0.08).

To examine the relationship between objective interoceptive accuracy (PAT) and state perceived stress (ESM item 5), a fixed effect model was performed with objective interoceptive accuracy (PAT) as the predictor and state perceived stress (ESM item 5) as the dependant variable. This revealed no significant relationship in the interoceptive group (β = -0.045 (-1.272 – 1.181), SE = 0.607, t(40.227) = -0.075, p = 0.941), or the auditory group (β = -0.135 (-0.871 – 0.602), SE = 0.364, t(40.573) = -0.369, p = 0.714). Similarly, a fixed effect model performed with objective interoceptive accuracy (PAT) as the predictor and state stressors (ESM item 6) as the dependant variable demonstrated no significant relationship in the interoceptive group (β = -0.311 (-1.416 – 0.794), SE = 0.548, t(42.423) = -0.568, p = 0.573) or the auditory group (β = -0.221 (-0.754 – 0.312), SE = 0.264, t(42.438) = -0.837, p = 0.407). In terms of the control measure, no significant relationship was observed between performance on the control task and state perceived stress (ESM item 5) for the interoceptive group (β = -0.848 (-3.089 – 1.392), SE = 1.109, t(40.435) = -0.765, p = 0.449), or the auditory group (β = -0.048 (-0.983 – 0.887), SE = 0.464, t(43.593) = -0.104, p = 0.918). No significant relationship was observed between performance on the control task and state stressors (ESM item 6) for the interoceptive group (β = -0.938 (-3.041 – 1.165), SE = 1.041, t(40.591) = -0.901, p = 0.373) or auditory group (β = -0.076 (-0.895 – 0.743), SE = 0.406, t(44.125) = -0.188, p = 0.852).

Relationship between trait interoception and stress

Regarding the relationship between trait interoception and trait stress, a negative relationship was observed between trait interoceptive attention (IATS) and physiological stress (PCA Factor 1; r = -0.206, p = 0.029), indicating that higher levels of stress reactivity were associated with higher perceived attention to internal sensations, as low levels of HRV reflect higher stress (Table 3). Similarly, a positive relationship was observed between trait interoceptive attention (IATS) and self-reported stress (PCA Factor 2; r = 0.315, p = 0.002), suggesting that higher levels of self-reported stress were associated with higher perceived attention to internal sensations. A significant negative relationship was also observed between trait interoceptive accuracy (IAS) and self-reported stress (PCA Factor 2; r = -0.22, p =

0.022), but not physiological stress (PCA Factor 1; r = -0.029, p = 0.397), indicating that higher levels of self-reported stress were associated with lower perceived interoceptive accuracy. R-to-z tests demonstrated that the size of correlations was significantly different between trait interoceptive measures (IAS and IATS) and self-reported stress (PCA Factor 2; z = -3.604, p < 0.001), but not physiological stress (PCA Factor 1; z = -1.158, p = 0.123), whereby the relationship between trait interoceptive attention (IATS) and self-reported stress (PCA Factor 2) was greater than the relationship between trait interoceptive accuracy (IAS) and self-reported stress (PCA Factor 2).

A fixed effects analysis performed with state perceived stress (ESM item 5) as the dependant variable and trait interoceptive attention (IATS) as the predictor variable demonstrated no significant relationship between trait interoceptive attention (IATS) and state perceived stress (ESM item 5) for the interoceptive group (β = 0.009 (-0.006 – 0.023), SE = 0.007, t(42.007) = 1.177, p = 0.246), or auditory group (β = 0.004 (-0.008 – 0.017), SE = 0.006, t(39.112) = 0.694, p = 0.492). Similarly, no significant relationship was observed between state stressors (ESM item 6) and trait interoceptive attention (IATS) for the interoceptive group (β = 0.004 (-0.01 – 0.018), SE = 0.007, t(42.097) = 0.563, p = 0.563) or the auditory group (β = 0.005 (-0.004 – 0.014), SE = 0.004, t(39.209) = 1.062, p = 0.295).

Regarding the relationship between state perceived stress (ESM item 5) and trait interoceptive accuracy (IAS), no significant relationship was observed for the interoceptive group (β = -0.001 (-0.02 – 0.018), SE = 0.009, t(41.108) = -0.11, p = 0.913), or the auditory group (β = -0.005 (-0.021 – 0.011), SE = 0.008, t(38.3996) = -0.591, p = 0.558). A fixed effects analysis with state stressors (ESM item 6) as the dependant variable and trait interoceptive accuracy (IAS) as the predictor demonstrated no significant relationship for the interoceptive group (β = -0.001 (-0.018 – 0.017), SE = 0.009, t(41.279) = -0.091, p = 0.928) or the auditory group (β = -0.004 (-0.015 – 0.007), SE = 0.006, t(38.016) = -0.727, p = 0.472).

Relationship between state interoceptive attention and stress

A fixed effects analysis revealed a significant relationship between state attention (ESM item 3) and state perceived stress (ESM item 5) for the interoceptive group (β = 0.070 (0.043 - 0.098), SE = 0.014, t(2467.048) = 5.101, p < 0.001), but not for the auditory group (β = -0.015 (-0.04 – 0.012), SE = 0.014, t(2338.596) = -1.095, p = 0.274). Similarly, a significant relationship was observed between state stressors (ESM item 6) and state attention (ESM item 3) for the interoceptive group (β = 0.117 (0.061 – 0.174), SE = 0.029, t(2459.710) = 4.071, p < 0.001), but not the auditory group (β = 0.005 (-0.058 – 0.067), SE = 0.032, t(2362.849) = 0.147, p = 0.883).

Regarding the association between state attention (ESM item 3) and physiological stress (PCA Factor 1), no significant relationship was observed for the interoceptive group (β = -0.038 (-0.292 – 0.216), SE = 0.126, t(38.909) = -0.301, p = 0.765), or the auditory group (β = 0.017 (-0.223 – 0.258), SE = 0.119, t(40.105) = 0.145, p = 0.886). Finally, no significant relationship was observed between self-reported stress (PCA Factor 2) and state attention (ESM item 3) for the interoceptive group (β = 0.174 (-0.144 – 0.493), SE = 0.157, t(39.01) = 1.109, p = 0.274), or auditory group (β = 0.159 (-0.063 – 0.381), SE = 0.11, t(40.519) = 1.445, p = 0.156).

Sex differences

Please see Appendix N for the correlation matrix summarising the exploratory analyses of sex differences. Post hoc power calculations demonstrated that the study was underpowered to detect sex differences (Power = 0.67), and a sample size of 132 (66 per condition) would be required to obtain a sufficient power of 0.8. Hence, these results should be treated with caution. Although some evidence for sex differences between trait measures of interoception (IAS and IATS) and stress (PCA factors 1 and 2) were observed, r-to-z tests demonstrated that these differences were not significant. For ESM measures, similar patterns were observed for both males and females (see Appendix O) across the majority of comparisons. However, a significant negative relationship was observed between state stressors (ESM) and the objective measure of interoceptive accuracy (PAT) for males in the auditory group ($\beta = -0.697$ (1.353; -0.04), $SE = 0.315$, $t(19.714) = -2.215$, $p = 0.039$), but not in the interoceptive group (see Appendix Q).

Discussion

The current study aimed to investigate the relationship between different facets of interoception and stress. Results appear to support a relationship between interoception and stress, although the mechanisms underpinning this relationship are complicated by the different measures employed. In terms of the relationship between stress measures, we observed little correspondence between the different measures of stress across measurement types where state measures related to each other, self-report measures related to each other, and physiological measures related to each other, but no relationships were observed across measures. In terms of the relationship between interoception measures, whilst we observed no relationship across measures of interoceptive attention and accuracy, surprising relationships were observed within dimensions between measures thought to assess accuracy, and different measures thought to assess interoceptive attention. In terms of the relationship between interoception and stress, whilst state measures generally related to each other, and some relationships were observed between trait measures, little correspondence was observed when comparing state to trait measures. These results are discussed in turn below.

First, a PCA performed with the stress measures demonstrated that the measures loaded onto two distinct components that separated physiological and self-report measures of stress. Measures of self-reported stress were related, as well as measures of physiological stress, as reflected by their common factor loadings, but no significant relationship was observed between the extracted components. This is consistent with previous work suggesting that stress is a multidimensional construct (Dorsey et al., 2022; Harkness et al., 2020). Regarding the relationship between state measures of stress, a significant positive relationship was observed between state perceived stress and state stressors as expected (Wright et al., 2020). In terms of the relationship between trait and state measures of stress, no significant relationships were observed. Importantly, ESM studies of stress have provided mixed results regarding the correspondence between state and trait measures of stress which seems to vary depending on the construct being assessed (Vaessen et al., 2015; Joshi et al., 2021; Goetz et al., 2024). Given the broad meaning of stress which encompasses many responses (i.e. perceived stress, chronic stress, stress response, etc.), it is likely that different measures of stress might be assessing different domains and facets of stress, leading to a small correspondence between measures. This highlights the importance of the multi-dimensional approach to the measurement of stress adopted here and in Chapter 1.

This study also provided the first test of the relationship between multiple measures of interoception. First, no relationship was observed between measures thought to assess dimensions of interoceptive accuracy (trait, self-reported and objective) and measures thought to assess interoceptive attention (trait and state) in line with previous findings suggesting that these two dimensions of interoception are dissociable (Gabriele et al., 2022; Murphy, Catmur, et al., 2019). However, surprising results were observed between measures thought to assess the same construct. Indeed, a small negative relationship was observed between trait self-reported interoceptive accuracy and the objective measure of interoceptive accuracy, suggesting that higher perceived interoceptive accuracy related to worse performance on the objective task of interoceptive accuracy. This is in contrast with previous work using the same measure which observed no relationship (Plans et al., 2021). Although the same pattern was observed with the control task, suggesting that this effect was not unique to interoception, these results indicate that individuals have little insight into their interoceptive ability (i.e., poor metacognition or interoceptive awareness; Garfinkel et al., 2015; Murphy, Catmur, et al., 2019; Plans et al., 2021). However, as the IAS asks participants to report on their beliefs regarding their accuracy of perceiving various internal signals, and objective accuracy dissociates across domains (Desmedt et al., 2023; Murphy et al., 2020), it is possible that these surprising results are due to the inclusion of various interoceptive domains in the IAS.

Regarding interoceptive attention, in contrast to previous literature that has observed small associations between state and trait measures of interoceptive attention (Poerio et al., 2024), a significant relationship was observed in the auditory ESM but not the interoceptive ESM group, suggesting that increased focus on auditory signals was related to higher self-perceived beliefs of increased attention to interoceptive signals. Although this result requires replication, a possible explanation lies in our approach. In Poerio et al. (2024) participants reported on their attention to 21 specific internal sensations matching those reported by the trait interoceptive attention measure, which may provide a more reliable measure of state attention to internal signals compared to a single broad item. Second, as Poerio et al. (2024) used a within subject design where participants reported on their attention to both auditory and internal signals (whilst we employed a between-subjects design) it is possible that reporting on these concurrently vs. separately changes attentional allocations. Future research is required to explore these surprising findings further.

In terms of the relationship between measures of stress and trait measures of interoception, consistent with previous work we observed that higher trait self-reported attention to interoceptive signals was associated with increased self-reported and physiological stress as measured using questionnaires and HRV, respectively (Cabrera et al., 2017; MacCormack et al., 2024). In contrast, higher self-reported accuracy appeared to only relate to lower levels of self-reported stress. Whilst some evidence of sex differences was observed consistent with previous research (Murphy, Viding, et al., 2019), this was not reliable and is thus not considered further given the study was underpowered to detect sex effects. As well as highlighting the importance of separating self-reported interoceptive accuracy and attention (Gabriele et al., 2022; Murphy, Catmur, et al., 2019), these results provide support for hypothesis two and partly for hypothesis three, suggesting that heightened attention to interoceptive cues, coupled with misinterpretation of those signals, may lead to an increase in stress-related physical symptoms (Joshi et al., 2021). Moreover, these data are also consistent with previous work suggesting that individuals who believe themselves to have greater interoceptive accuracy report less stress (see Chapter 1; MacCormack et al., 2024). Importantly, this was not observed for the objective measure of interoceptive accuracy which related to no measures of stress. Although somewhat inconsistent with previous research using older measures of cardiac interoceptive accuracy (Chapter 1), these results are in line with previous work using the PAT (Plans et al., 2021). As the IAS assesses beliefs regarding multiple interoceptive signals, it may be that stress relates to other objective measures of interoception but not cardiac interoceptive accuracy. Alternatively, it may be that state factors play a role. As objective interoceptive accuracy may be influenced by state factors (Höller et al., 2021; Plans et al., 2021; Wittkamp et al., 2018), and state factors also play a role in stress (Thorn et al., 2009), it may be that measuring interoceptive accuracy on a single occasion does not provide an adequate assessment of an individuals interoceptive ability (Murphy, 2024). Of course, given the little correspondance between beliefs and objective interoceptive accuracy (Plans et al., 2021), it may be that stress relates to one's beliefs about interoceptive accuracy, but not accuracy itself. Whether believing one's interoceptive accuracy to be greater is a protective factor remains unknown.

In terms of state measures of interoception and stress, a positive relationship was observed between attention to internal signals and both state stress measures, indicating that increased attention to internal signals is associated with elevated perceived levels of stress and increased appraisals of situations as stressful. This is consistent with prior evidence and models that propose that attention has a modulatory role in the relationship between interoception and stress (Schulz & Vögele, 2015). It could be hypothesised for this relationship to be bi-directional, as the experience of stress or exposure to stressors could activate the physiological stress response and enhance interoceptive signal strength, thus making it more salient for attentional processes to be directed at such signals. Similarly, attention to internal body signals, when combined with an altered body perception, could lead to interpreting normal sensations as threatening, thus increasing stress and generating more sensations (Schulz & Vögele, 2015). However, no correspondence was observed between trait and state measures of stress and interoception. Taken together with the aforementioned results suggesting some correspondence between trait measures of stress and trait measures of interoception, and correspondence with state measures of stress and state measures of interoception, these results are consistent with the aforementioned idea that state factors play a substantial role in the measurement of both interoception and stress (Höller et al., 2021; Thorn et al., 2009). Such observations may go some way to understanding mixed results in the literature regarding the relationship between interoception and stress and highlight a need to expand the ESM approach to examine relationships between interoceptive accuracy and stress using multiple, in the moment, measures.

Limitations

When interpreting these results, it is important to consider the limitations of the present study. First, it should be acknowledged that the sample size was comprised mostly of undergraduate students, which could affect the generalisability of results. As a recent study supports the suitability of the PAT for remote testing (Spooner et al., 2024), future studies could employ remote designs to collect more representative samples. Second, the ESM survey only included one item to assess state attention. This limited our capacity to assess whether the relationship between attention to internal signals and stress varies across domains and provides one explanation for our surprising finding that state auditory attention related to trait interoceptive attention (Poerio et al., 2024). As attention to internal body signals can have an adaptive or maladaptive function by facilitating self-regulation or enhancing symptom generation respectively (Trevisan et al., 2021), the inclusion of a single item also means that we were unable to explore whether the type of attention paid to internal signals relates to stress. Third, whilst we aimed to examine sex differences, our results were underpowered for these comparisons. Again, remote testing in the future may enable the recruitment of larger samples. Additionally, while we assessed interoceptive attention over time, we did not utilise state measures of other interoceptive dimensions. As state factors may play a role in other interoceptive processes (Plans et al., 2021), and in measures of stress (i.e. physiological measures), it is possible that some relationships were obscured by our methodological approach. Finally, whilst we aimed to assess multiple measures of stress (see Chapter 1), only two broad domains were assessed here, and we did not utilise an experimental design to examine causal relationships between interoception and stress. It is also worth noting that the questionnaires employed for the measurement of stress are subject to criticism regarding their validity (Brown et al., 1997; Harkness et al., 2020). Future research using more reliable measures of interoception and stress is therefore required to establish causality, and determine the mechanisms underpinning the relationship between interoception and stress.

Clinical implications

The clinical implications of this study are substantial, especially considering the increased clinical relevance of interoception based psychological interventions for numerous pathologies, including post-traumatic stress disorder and substance use disorders (Heim et al., 2023). These interventions target interoceptive processes to improve symptoms of mental health conditions, by increasing accuracy, focusing on interoceptive beliefs, or a combination of both via increased attention to body signals and reflection (Heim et al., 2023). The results of the study are indicative that different facets of interoception are distinct processes that interact with stress in various forms. Therefore, different interventions could be beneficial depending on the nature of the interaction between atypical interoception and stress symptoms. For instance, mindfulness based cognitive therapies could be useful for enhancing adaptive attention to internal sensations to facilitate self-regulation (Heim et al., 2023; Trevisan et al., 2021), while interoceptive training could target maladaptive attention to internal sensations thus reducing the generation of physical sensations stemming from the misinterpretation of such sensations (Quadt et al., 2021). On the other hand, interoceptive beliefs could be targeted with Interoceptive Exposure (IE) therapies aimed at changing catastrophic misinterpretations of the internal body sensations increasing stress (Ginat-Frolich et al., 2023). Additionally, due to the role of both interoception and stress in various physical and mental health conditions, interoception based interventions that target stress-related physical sensations could offer a transdiagnostic approach for the treatment of other conditions.

Conclusion

The present study found evidence of relationships between interoception and stress, highlighting correspondence between state measures, and between trait measures, but not across trait and state measures. Given the impact of state factors in both stress and interoceptive processes, future research should examine the relationship between multiple measures of interoception and stress over time.

Chapter 3. Integration, impact, and dissemination plan

This chapter will integrate the systematic review and empirical study by discussing their conceptualisation, based on limitations of existing research. Implications and reflections about the methodology and results are considered throughout, as well as some of the challenges encountered. Finally, a dissemination plan will be presented aimed at maximising the impact of both pieces of work.

Integration

Overall process and conceptualisation

First, it is important to acknowledge that interoception was a new research topic for me, so I started this project by informing myself about the evidence base regarding the relationship between interoception and stress. The learning curve was steep at first due to having to familiarise myself with new language and concepts, which was further hindered by discrepancies in the terminologies, tasks, and dimensions of interoception used by different research groups. Recent research has begun to address some of the most prominent methodological issues in interoceptive research through the development of new models and measures of interoception. This provided an exciting opportunity for me to contribute to research in the field of interoception by employing the newly improved measures and theoretical frameworks.

One specific area of interoception that captured my attention concerned its relationship with wellbeing and pathology. I was previously unaware of the involvement of interoception in numerous mental and physical health conditions. However, the mechanisms underlying these relationships seemed elusive, possibly reflecting the methodological limitations of existing work. A prominent mental health difficulty related to interoceptive processes is stress, which is also associated with the development and maintenance of other physical and mental health conditions. As I deepened my understanding of the theoretical work and evidence base linking interoception and stress, it became apparent that work on both areas presents significant methodological challenges which has limited our understanding of the mechanisms underlying this relationship, if there is indeed a relationship at all. Therefore, this project sought to investigate the relationship between stress and interoception by synthesising the results of published research and empirically exploring this relationship with improved measures of interoception.

Integration of meta-analysis and empirical projects

The results of the meta-analysis were generally consistent with the presence of a relationship between cardiac interoceptive accuracy and different domains of stress (acute physical stress, chronic self-reported stress, and physiological stress response). Nevertheless, an important limitation of the meta-analysis was the inclusion of studies employing the Heartbeat Counting Task (HCT) as a measure of cardiac interoceptive accuracy. The HCT has been subject to considerable criticism due to the potential cofounding effects of prior knowledge about one's own heartrate leading to false positives (Desmedt et al., 2023). Although the meta-analysis also demonstrated some preliminary differences regarding how the HCT and other tasks of cardiac interoceptive accuracy (i.e. the Heartbeat Detection Task, HDT) relate to stress, the number of studies that employed the HDT was too small to draw any definitive conclusions. Therefore, although the findings supported a relationship between interoception and stress, the measure of interoceptive accuracy used by the majority of studies identified by the systematic review limited the conclusions that could be drawn (Desmedt et al., 2023).

The empirical study aimed to follow up on these results by exploring the relationship between interoception and stress with a more psychometrically valid measure of cardiac interoceptive accuracy, the Phase Adjustment Task (PAT), which is reported to overcome the limitations of existing tools (Plans et al., 2021; Desmedt et al., 2023). Additionally, this study also aimed to broaden our understanding of the relationship between interoception and stress by including multiple measures tapping different interoceptive and stress dimensions. Within this, we sought to examine the role of both state and trait interoceptive attention. The results of the empirical study supported the use of a multi-dimensional approach for measuring interoception and stress, as the relationship between measures appeared to differ for different dimensions of interoception and stress, with little correspondence observed between trait and state measures.

Challenges

First, it is important to acknowledge that the current study was my first experience conducting a systematic literature review and meta-analysis. The abstract and full text screening process proved to be time consuming and there was a considerable number of relevant papers that did not directly report the effect sizes I required. I was particularly struck by the lack of studies making relevant data available in open science websites, as it hinders the advancement of scientific research by limiting opportunities for secondary data analyses like meta-analyses. In my case, a considerable amount of time was devoted to individually contact authors from relevant studies to request data. Unfortunately, I was unable to access some of the data, as some authors did not respond to requests, or the data was no longer accessible due to the time since publication or due to researchers moving institutions. Hence, the final sample of studies included in my meta-analysis was small, which led to increased heterogeneity, publication bias and the influence of single studies, ultimately limiting the ability to draw definitive conclusions. This challenge highlighted the importance of making relevant data accessible to support continued advances in scientific research. In order to address this, I aim to make my data available, therefore fostering collaboration and transparency in my research projects.

Another challenge was related to testing participants face to face at the Royal Holloway lab. Although I enjoyed being involved in gathering data and testing participants in person, balancing the multiple demands of clinical placements, along with travelling to Royal Holloway to test participants proved challenging at times. Testing at the university lab also posed a challenge for recruitment, as only students were able to attend the lab twice, therefore limiting our ability to use a more representative sampling strategy. Although we were able to recruit many students at first, recruitment became more challenging in November, once students had collected their required credits. To overcome this challenge, we decided to start testing participants in other University of London locations in central London and offer monetary vouchers for participation, which was helpful for recruiting more participants including those who were not students. However, we were still unable to recruit an equal number of males and females for exploring sex effects, and hence analyses were underpowered to detect meaningful differences. Although the decision to test in person was based on a pilot study suggesting less attrition for the experience sampling measure when participants attended in person, this limitation could be overcome by offering participants an online orientation session prior to starting testing. Additionally, a study completed recently demonstrated that the quality of the Phase Adjustment Task is comparable when administered in person or online (Spooner et al., 2024). This provides an exciting new possibility for future research, opening the opportunity to collect larger and more representative samples to answer questions of interest.

Finally, another challenge relates to service user involvement in the process. As the methodology for the empirical study directly stemmed from the new measures and methodological frameworks developed to address limitations of previous research on interoception, it was not possible to involve service users in the development of the project or methodologies. The study mostly included undergraduate students at Royal Holloway, so I am hoping to involve service users in the dissemination process. I believe the contribution of service users for disseminating the findings will be highly valuable as they might be able to provide guidance regarding which channels to use for disseminating the findings to the public, as well as making sure the language is accessible for any population interested on the topic. I am mindful that co-production in research can be challenging, as my previous attempts to co-produce in other research projects faced barriers, especially due to not having established platforms that allow safe co-production. I hope to continue being mindful of the importance of service-user involvement in both research and service development and contribute to the development of systems that will facilitate more meaningful service user involvement in the future.

Personal reflections

First, I would like to acknowledge that being part of a research team was invaluable for completing this study, as it allowed me to learn from other people's unique set of skills and experiences. Additionally, supporting each other during the project setting, data collection and data preparation stages was helpful for managing the workload and any challenges effectively. While balancing two research projects alongside my clinical responsibilities occasionally posed challenges, I overall enjoyed engaging in research and learning how to navigate these two projects. I believe this to be partly due to the support I received from my supervisor and peers, who made the experience interesting and less isolating.

An unexpected area of learning was the use of the programming language R for performing the meta-analysis, as well as scoring data and merging databases for the empirical project. I was inexperienced in the use of any programming language before my involvement in this project, so learning this skill was a particularly challenging but rewarding endeavour. I dedicated a substantial amount of time to understanding the programming language, and realised how useful this can be for data processing, especially when multiple databases are collected from different sources (i.e. Qualtrics, ESM, PAT). This is a skill that I would like to further develop in my future work as I believe it would greatly benefit my practice in clinical psychology as a scientist-practitioner.

Finally, reading about and understanding the complex interaction between interoception and stress and their relation to psychopathology was very interesting clinically, especially during my placements in neurodevelopmental and chronic pain services, given the focus on populations known to experience issues relating to both interoception and stress (Hatfield et al., 2019; Murphy et al., 2017; Schulz & Vögele, 2015). Research about interoception and stress and their interaction with mental and physical health (Brewer et al., 2021; Schulz & Vögele, 2015) was helpful for making mind body links and for developing more complex conceptualisations of pathology that differ from disorder specific formulations. I believe this approach to be helpful for working in setting such as the NHS, where a large number of patients present with complex and often concomitant mental and physical health needs.

Impact

Research implications

There are many research implications stemming from this study. First, the development and validation of a momentary measure of interoceptive attention has important implications for the use of ecological measures in interoceptive research. Given our study supported the influence of state factors for both interoception and stress (Höller et al., 2021; Thorn et al., 2009), the findings highlight the need for future research to adopt momentary assessments of interoception and stress, alongside trait measures to determine the mechanisms underlying their intricate relationship. The current study facilitated advancements in momentary assessments of interoception and stress by validating the use of experience sampling methodologies, extending work by other studies employing similar methodologies to assess cardiac interoceptive accuracy and attention to multiple interoceptive domains (Höller et al., 2021; Poerio et al., 2024).

On the other hand, the results of the meta-analysis and empirical study provided supportive evidence for both interoception and stress being multi-dimensional processes with various interactions across domains and facets. This has important methodological implications for future research as it supports the use of multi-measure approaches for the assessment of the relationship between interoception and stress. Given the methodological issues that have hampered progress in both interoception and stress research (Desmedt et al., 2023; Harkness et al., 2020), these findings provide a direction for future research to overcome such limitations.

Clinical implications

Regarding the clinical implications, the meta-analysis and empirical study suggested a relationship between interoception and stress, although the mechanisms underpinning the relationship remain elusive due to the multidimensional nature of both interoception and stress. Some promising newly developed clinical interventions for targeting different dimensions of interoception and its relevance to stress were discussed in Chapters 1 and 2. These interventions could be helpful for developing transdiagnostic approaches for the treatment of different mental and physical health conditions, which could be beneficial for overcoming some of the limitations of traditional diagnostic taxonomy based approaches (Dalgleish et al., 2020).

Another important clinical implication of this research relates to the more accessible and less invasive measures that could be employed in clinical settings. For example, the

Phase Adjustment Task (PAT) or experience sampling measures are easily accessible on mobile phone devices and could be employed in clinical interventions, for instance Cognitive Behaviour Therapy (CBT) interventions focused on targeting beliefs about interoceptive abilities and attention consistent with its use in research (Höller et al., 2021). Clinicians and researchers could focus on developing guidelines and protocols for the safe and effective use of these technologies in psychological interventions.

Personal implications

I believe that engaging in this research significantly contributed to my personal and professional development. First, I enjoyed being able to divide my time between clinical and research duties, as it allowed me to reflect about the clinical implications of my research, as well as broadening my knowledge of the mechanisms underpinning my clinical work. Being able to work on a project that improved the methodological framework for the study of interoception and stress was also helpful for learning how to critically evaluate research methods when reviewing relevant studies for my clinical practice. This also highlighted the importance of employing robust measures and protocols to be able to draw strong conclusions from findings. Additionally, performing a systematic review and meta-analysis was helpful for widening my understanding of the strengths and limitations of synthesising the evidence using such approaches. Considering clinical guidelines are based on systematic reviews of the published evidence (NICE, 2014), I believe that knowledge about these methodologies is invaluable for critically appraising the available guidance and evidence base to support my clinical work.

On the other hand, researching the complex relationship between interoception and stress and how it relates to the development and maintenance of multiple physical and mental health conditions was also striking on a personal level, especially considering the stressful nature and demands of both clinical and research work. A particular area of personal interest was the role of attentional processes in the relationship between interoception and stress because I believe this to be a more accessible target for intervention than, for example, dimensions regarding interoceptive accuracy. I reflected on the potential benefits of simple skills such as mindfulness practices for maintaining wellbeing during periods of heightened stress by developing more adaptive attentional styles to target the complex interaction between interoception and stress (Gibson, 2019).

Dissemination

In order to enhance the impact of the findings, both the meta-analysis and empirical project will be disseminated through various channels. First, the findings of the meta-analysis and empirical study were presented to clinical psychology students and course staff at Royal Holloway. The aim was twofold: to disseminate the acquired knowledge from the research to practising members of the clinical psychology workforce, and to motivate students to pursue research in this field and contribute to the evidence base regarding the relationship between interoception and stress.

The meta-analysis will be submitted to academic journals, for example, Neuroscience & Biobehavioural Reviews or Psychonomic Bulletin & Review. The results from the empirical project will also be submitted to academic journals (for example, British Journal of Clinical Psychology, JAMA Psychiatry) as part of a wider study, including other domains of mental health to maximise its impact. This empirical work has also supported two publications currently under review in the Scientific Reports and Psychophysiology journals. One further study examining the relationship between interoceptive dimensions will also be submitted for publication in an academic journal. Journals targeted will include Biological Psychology and Psychophysiology.

Finally, the insights derived from the projects will be disseminated via my supervisor's active webpage www.jennifermurphylab.com, where the primary findings will be outlined and made available to any audience interested in interoceptive research. The project will also be submitted to the Pure Research Portal used at Royal Holloway www.pure.royalholloway.ac.uk, where it will be openly accessible to students and researchers alike. As my supervisor has previously written articles for The Conversation www.theconversation.com/uk , a lay article could also be submitted after publication in a peer-reviewed journal.

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Appendix A.

Table 9.

Table summarising the characteristics of studies employing the HDT task.

Author	N (F/M)	Age (M)	Clinical group	IAc measure	Type of measure	Stress measure	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	Adjusted r	Composite ES	Quality
Schulz et al. (2013)	42 (29/13)	22.95	None	HDT (visual)	Acute cognitive and physical stressor	SECPT	High score is better accuracy	High score is more stress	n^2	0.13	0.361	0.13	83%
				HDT (auditory)	Acute cognitive and physical stressor	SECPT	High score is better accuracy	High score is more stress	t	-0.48	-0.1		83%
Wittkamp et al. (2018)	59 (40/19)	23.4	None	HDT (auditory)	Acute cognitive stressor	CRTT	High score is better accuracy	High score is more stress	n^2	0.07	0.265	0.265	85%
Plans et al. (2021)	124 (70/54)	26.5	None	PAT	Self-report measure	DASS	High score is better accuracy	High score is more stress	d	0.3	0.148	0.148	82%
Schulz et al. (2013)	42 (29/13)	22.95	None	HDT (auditory)	Self-report measure	TICS	High score is better accuracy	High score is more stress	r	0.09	0.09	0.115	83%

				HDT (Visual)	Self-report measure	TICS	High score is better accuracy	High score is more stress	r	0.14	0.14		
Plans et al. (2021)	124 (70/54)	26.5	None	PAT	Physiological stress response	SDNN	High score is better accuracy	High score is less stress	d	0.2	-0.1	-0.075	82%
				PAT	Physiological stress response	pNN50	High score is better accuracy	High score is less stress	d	0.17	-0.085		
				PAT	Physiological stress response	RMSSD	High score is better accuracy	High score is less stress	d	0.08	-0.04		
Fairclough et al. (2007)	40 (20/20)	25.55	None	HDT (auditory)	Physiological stress response	HRV	High score is better accuracy	High score is less stress	r	0.14	-0.14	-0.14	92%

Abbreviations: IAc Interoceptive accuracy, ES Effect Size, r Pearson's correlation coefficient, HDT Heartbeat Detection Task, PAT Phase Adjustment Task, SECPT Socially Evaluated Cold Pressor, CRTT Choice Reaction Time Task, DASS Depression Anxiety Stress Scale, TICS Trier Inventory for the Assessment of Chronic Stress, SDNN Standard deviation of all normal RR (NN) intervals during a 24-hour period, pNN50 mean number of times an hour in which the change in successive normal sinus intervals exceeds 50 milliseconds, RMSSD Root mean square of successive differences between normal heartbeats, HRV Heart Rate Variability, n^2 partial eta squared, d Cohen's d.

Appendix B.

Description and results of meta-analyses employing the HDT task.

The HDT tasks included in the meta-analysis showed variability as one study focused on visual stimuli (Wittkamp et al., 2018), one on auditory stimuli (Fairclough & Goodwin, 2007), one on both (Schulz et al., 2013) and another one on a new task of cardiac interoceptive accuracy called the Phase Adjustment Task (PAT), which uses auditory exteroceptive stimuli (Plans et al., 2021). All the visual and auditory tasks were based on the original Whitehead HDT task, where participants are instructed to judge whether exteroceptive stimuli (visual/auditory) were presented synchronously or asynchronously to their heartbeats. The length of trials used by different studies also showed large variability, as trials differed from 10 (Fairclough & Goodwin, 2007), to 20 (Schulz et al., 2013) and up to 40 (Wittkamp et al., 2018). Two studies offered participants 5 training trials (Schulz et al., 2013; Whitehead et al., 1977), with no training trial offered by the third study (Fairclough & Goodwin, 2007). All studies calculated the data using the following formula derived from signal detection theory:

Discrimination (d′) = $Zhit\ rate - Zfalse\ alarm\ rate$

Following this formula, higher scores would indicate better discrimination and therefore higher interoceptive accuracy, whereas lower scores would be indicative of lower discrimination and a higher false alarm rate.

Finally, one study included a new HDT task, the Phase Adjustment Task (PAT), where participants were instructed to rotate a visual dial in the screen of a smartphone until they perceived auditory tones to be synchronous to their heartrate (Plans et al., 2021). Participants completed two practice trials followed by 20 trials. Results for this task were analysed using the following calculation:

Figure 17.

Equation for scoring the PAT.

$$Consistency\,(d, p) = \frac{1}{n} mod\left(\sum_{j=1}^{n} e^{i2\pi\frac{dj}{pj}}\right)$$

Note. $\underline{d}$ *= selected delay,* $\underline{p}$ *= periodic function of the period,* $\underline{n}$ *= the number of considered angles.*

The results ranged from 0 to 1, where 1 indicated absolute consistency of participants' responses over trials, while numbers close to 0 indicated that angles were positioned randomly and therefore interoceptive accuracy was lower.

Results

Acute cognitive stress

Figure 18.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of acute cognitive stress and HDT.

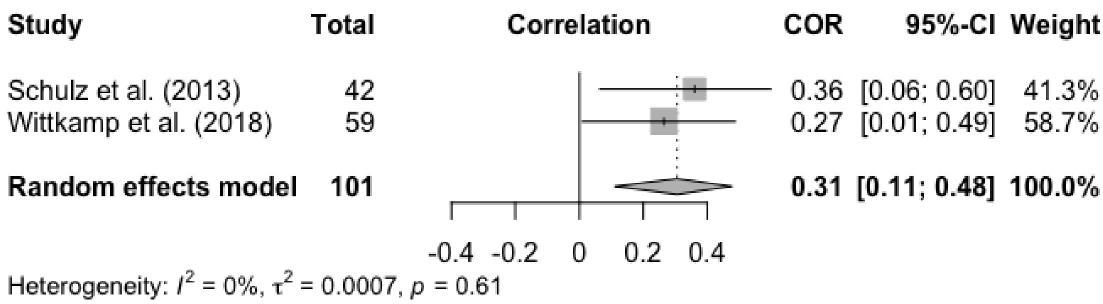
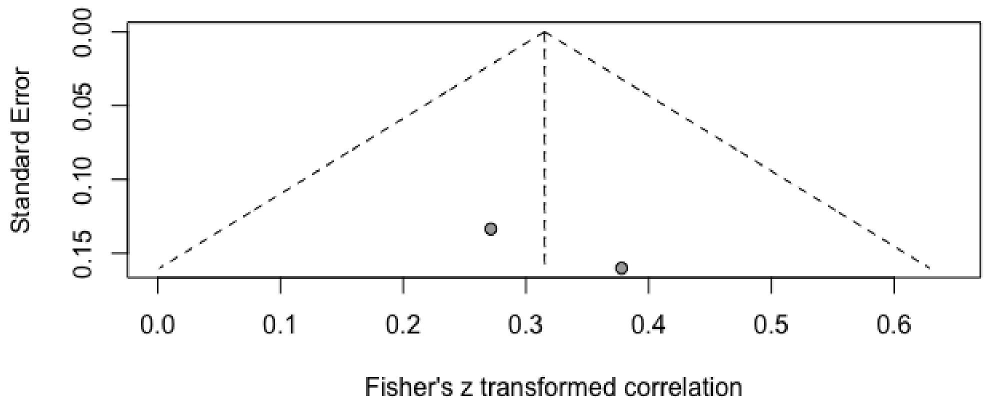


Figure 19.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of acute cognitive stress and HDT.



Chronic self-reported stress

Figure 20.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of chronic self-reported stress and HDT.

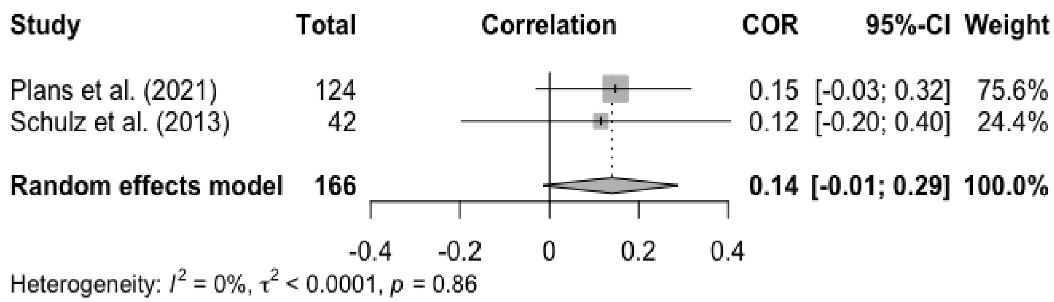
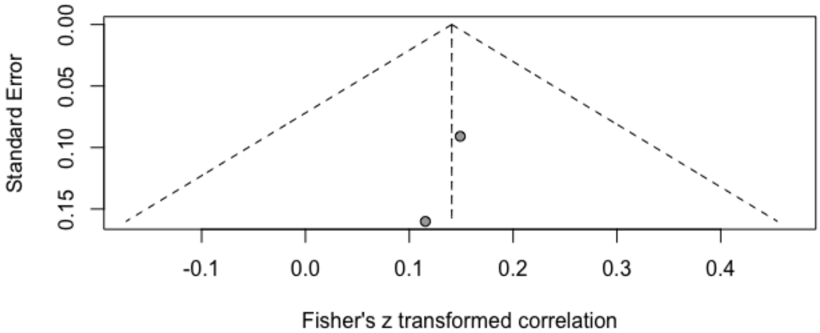


Figure 21.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of chronic self-reported stress and HDT.



Physiological stress response

Figure 22.

Forest plot showing the correlation, confidence intervals and weight of the studies included in the analysis and the pooled effect size of physiological stress response and HDT.

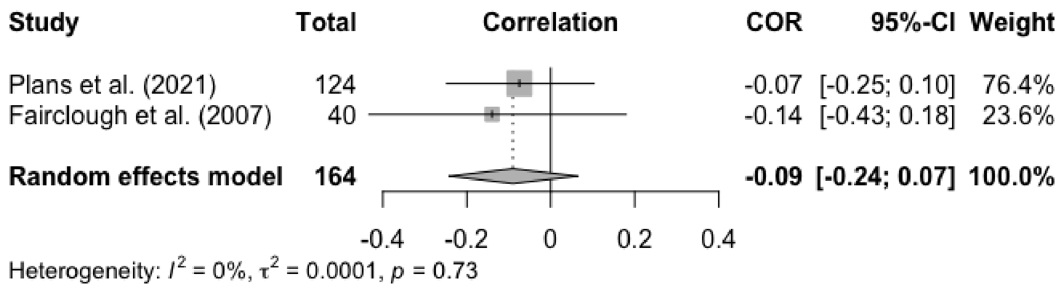
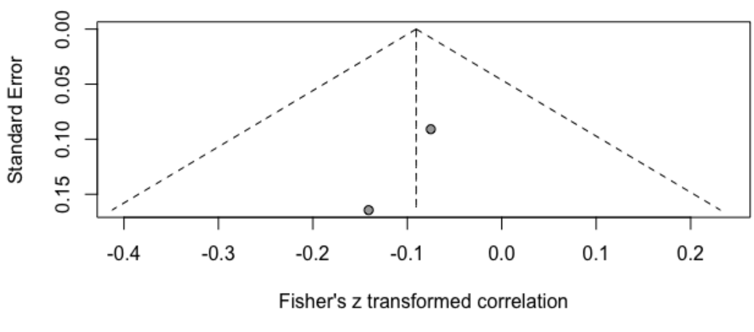


Figure 23.

Funnel plot showing the relationship between Fisher's z transformed correlation and the standard error of each study included in the meta-analysis of physiological stress response and HDT.



Appendix C.

Table 10.

Table summarising the characteristics of studies employing the HCT task divided by sex.

Author (year)	Sex	N	Clinical group	Type of measure	Stress measure	Direction of interoceptive measure	Direction of stress measure	ES Type	Extracted ES	r	Adjusted r	Composite ES
Schenk et al. (2020)	Male	13	None	Acute physical stressor	SECPT	High score is better accuracy	High score is more stress	d	-1.039	-0.461	-0.461	-0.461
	Female	35	None	Acute physical stressor	SECPT	High score is better accuracy	High score is more stress	d	-1.024	-0.456	-0.456	-0.456
Schulz et al. (2013)	Male	6	None	Acute physical stressor	SECPT	High score is better accuracy	High score is more stress	d	0.267	0.133	0.133	0.133
	Female	15	None	Acute physical stressor	SECPT	High score is better accuracy	High score is more stress	d	0.067	0.033	0.033	0.033
Maeda et al. (2019)	Male	16	None	Acute cognitive stressor	TSST	High score is better accuracy	High score is more stress	t	-0.396	0.102	0.102	0.102
	Female	20	None	Acute cognitive stressor	TSST	High score is better accuracy	High score is more stress	t	-0.907	-0.203	-0.203	-0.203

Schenk et al. (2020)	Male	13	None	Acute cognitive stressor	SECPT	High score is better accuracy	High score is more stress	d	-1.039	-0.461	-0.461	-0.461
	Female	35	None	Acute cognitive stressor	SECPT	High score is better accuracy	High score is more stress	d	-1.024	-0.456	-0.456	-0.456
Schulz et al. (2013)	Male	6	None	Acute cognitive stressor	SECPT	High score is better accuracy	High score is more stress	d	0.267	0.133	0.133	0.133
	Female	15	None	Acute cognitive stressor	SECPT	High score is better accuracy	High score is more stress	d	0.067	0.033	0.033	0.033
Wittkamp et al. (2018)	Male	19	None	Acute cognitive stressor	CRTT	High score is better accuracy	High score is more stress	n^2	0.140	0.374	0.374	0.374
	Female	40	None	Acute cognitive stressor	CRTT	High score is better accuracy	High score is more stress	n^2	0.180	0.424	0.424	0.424
Agostinho et al. (2019)	Male	29	None	Self-report measure	PSS	High score is better accuracy	High score is more stress	r	-0.004	-0.004	-0.004	-0.004
	Female	31	None	Self-report measure	PSS	High score is better accuracy	High score is more stress	r	-0.149	-0.149	-0.149	-0.149

Murphy et al. (2018)	Male	47	None	Self-report measure	DASS	High score is better accuracy	High score is more stress	r	-0.279	-0.279	-0.279	-0.279
	Female	73	None	Self-report measure	DASS	High score is better accuracy	High score is more stress	r	-0.285	-0.285	-0.285	-0.285
Lima-Araújo et al. (2022)	Male	20	None	Self-report measure	PSS	High score is better accuracy	High score is more stress	r	0.198	0.198	0.198	0.198
	Female	20	None	Self-report measure	PSS	High score is better accuracy	High score is more stress	r	0.079	0.079	0.079	0.079
Schulz et al. (2013)	Male	5	None	Self-report measure	TICS	High score is better accuracy	High score is more stress	r	0.645	0.645	0.645	0.645
	Female	15	None	Self-report measure	TICS	High score is better accuracy	High score is more stress	r	-0.025	-0.025	-0.025	-0.025
Schenk et al. (2020)	Male	13	None	Self-report measure	Work overload (TICS)	High score is better accuracy	High score is more stress	r	0.043	0.015	0.015	0.015
				Self-report measure	Social overload (TICS)	High score is better accuracy	High score is more stress	r	0.115			

			Self-report measure	Pressure to perform (TICS)	High score is better accuracy	High score is more stress	r	0.014			
			Self-report measure	Work discontent (TICS)	High score is better accuracy	High score is more stress	r	-0.066			
			Self-report measure	Excessive demands at work (TICS)	High score is better accuracy	High score is more stress	r	-0.015			
			Self-report measure	Lack of social recognitio n (TICS)	High score is better accuracy	High score is more stress	r	0.048			
			Self-report measure	Social tensions (TICS)	High score is better accuracy	High score is more stress	r	-0.086			
			Self-report measure	Social isolation (TICS)	High score is better accuracy	High score is more stress	r	-0.025			
			Self-report measure	Chronic worrying (TICS)	High score is better accuracy	High score is more stress	r	0.106			
Female	35	None	Self-report measure	Work overload (TICS)	High score is better accuracy	High score is more stress	r	0.054	-0.154	-0.154	-0.154

Self-report measure	Social overload (TICS)	High score is better accuracy	High score is more stress	r	-0.058
Self-report measure	Pressure to perform (TICS)	High score is better accuracy	High score is more stress	r	-0.017
Self-report measure	Work discontent (TICS)	High score is better accuracy	High score is more stress	r	-0.266
Self-report measure	Excessive demands at work (TICS)	High score is better accuracy	High score is more stress	r	-0.21
Self-report measure	Lack of social recognitio n (TICS)	High score is better accuracy	High score is more stress	r	-0.18
Self-report measure	Social tensions (TICS)	High score is better accuracy	High score is more stress	r	-0.124
Self-report measure	Social isolation (TICS)	High score is better accuracy	High score is more stress	r	-0.242
Self-report measure	Chronic worrying (TICS)	High score is better accuracy	High score is more stress	r	-0.339

Schulz et al. (2022)	Male	58	MDD	Self-report measure	CTQ	High score is better accuracy	High score is more stress	r	0.124	0.124	0.124	0.124
	Female	56	MDD	Self-report measure	CTQ	High score is better accuracy	High score is more stress	r	-0.239	-0.239	-0.239	-0.239
Lima-Araújo et al. (2022)	Male	20	None	Physiological stress response	Cortisol	High score is better accuracy	High score is more stress	r	0.210	0.210	0.210	0.210
	Female	20	None	Physiological stress response	Cortisol	High score is better accuracy	High score is more stress	r	-0.070	-0.070	-0.070	-0.070
Maeda et al. (2019)	Male	16	None	Physiological stress response	Salivary cortisol	High score is better accuracy	High score is more stress	r	-0.295	-0.295	-0.295	-0.295
	Female	20	None	Physiological stress response	Salivary cortisol	High score is better accuracy	High score is more stress	r	0.055	0.055	0.055	0.055
Williams et al. (2020)	Male	9	FND	Physiological stress response	Cardiosympathetic index	High score is better accuracy	High score is less stress	r	-0.065	-0.065	0.065	0.143
	Male			Physiological stress response	Cardiovagal index	High score is better accuracy	High score is less stress	r	-0.221	-0.221	0.221	

	Female	44	FND	Physiological stress response	Cardiosympathetic index	High score is better accuracy	High score is less stress	r	-0.089	-0.089	0.089	-0.250
	Female			Physiological stress response	Cardiovagal index	High score is better accuracy	High score is less stress	r	0.589	0.589	-0.589	
Schenk et al. (2020)	Male	13	None	Physiological stress response	Cortisol	High score is better accuracy	High score is more stress	r	-0.152	-0.152	-0.152	-0.152
	Female	35	None	Physiological stress response	Cortisol	High score is better accuracy	High score is more stress	r	-0.05	-0.05	-0.05	-0.05

Abbreviations: ES Effect Size, r Pearson's correlation coefficient, MDD Major Depressive Disorder, SECPT Socially Evaluated Cold Pressor, TSST Trier Social Stress Test, CRTT Choice Reaction Time Task, PSS Perceived Stress Scale, DASS Depression Anxiety Stress Scale, TICS Trier Inventory for the Assessment of Chronic Stress, CTQ Childhood Trauma Questionnaire, d Cohen's d, t Student's t distribution, n^2 partial eta squared.

Appendix D.

Results of meta-analyses investigating the relationship between stress and cardiac interoceptive accuracy in studies employing the HCT task divided by sex.

Table 11.

Meta-analysis of acute physical stress by sex.

Sex	k	ZCOR	SE	CI	p	Q	I^2	I^2 lower
Female	2	- 0.281	0.252	- 0.776 - 0.214	0.265	2.404	0.58	0
Male	2	0.314	0.34	- 0.981 - 0.352	0.355	0.923	0	NA

Abbreviations: k number of studies, ZCOR Fisher's r-to-z transformed correlation coefficient, SE Standard Error, CI Confidence Interval, p probability value, Q Cochran's Q test.

Test of between group differences: Q = 0.006, df = 1, p = 0.937.

Table 12.

Meta-analysis of acute cognitive stress by sex.

Sex	k	ZCOR	SE	CI	p	Q	I^2	I^2 lower
Female	4	- 0.049	0.209	- 0.458 - 0.360	0.815	16.01	0.81	0.51
Male	4	0.045	0.215	- 0.376 - 0.467	0.832	4.928	0.39	0

Abbreviations: k number of studies, ZCOR Fisher's r-to-z transformed correlation coefficient, SE Standard Error, CI Confidence Interval, p probability value, Q Cochran's Q test.

Test of between group differences: Q = 0.099, df = 1, p = 0.753.

Table 13.

Meta-analysis of chronic self-reported stress by sex.

Sex	**k**	**ZCOR**	**SE**	**CI**	**p**	**Q**	$\mathbf{I^2}$	$\mathbf{I^2}$ **lower**
Female	6	- 0.187	0.077	- 0.337 - 0.037	0.015	2.531	0	0
Male	6	0.017	0.124	- 0.227 - 0.260	0.893	6.327	0.21	0

Abbreviations: k number of studies, ZCOR Fisher's r-to-z transformed correlation coefficient, SE Standard Error, CI Confidence Interval, p probability value, Q Cochran's Q test.

Test of between group differences: Q = 1.945, df = 1, p = 0.163.

Table 14.

Meta-analysis of physiological stress response by sex.

Sex	**k**	**ZCOR**	**SE**	**CI**	**p**	**Q**	$\mathbf{I^2}$	$\mathbf{I^2}$ **lower**
Female	4	- 0.049	0.209	- 0.458 - 0.360	0.815	16.008	0.81	0.51
Male	4	0.045	0.215	- 0.376 - 0.467	0.832	4.928	0.39	0

Abbreviations: k number of studies, ZCOR Fisher's r-to-z transformed correlation coefficient, SE Standard Error, CI Confidence Interval, p probability value, Q Cochran's Q test.

Test of between group differences: Q = 0.099, df = 1, p = 0.753.

Appendix E.

Participant information sheet.

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Jennifer Murphy
Lecturer

Jennifer.murphy@rhul.ac.uk

Research information sheet

Interoceptive attention: an experience sampling study

Dear participant,

Welcome to this study. We are seeking your participation in an exciting new project, which examines individual differences in the amount of attention we pay to signals in our body and the environment and how this relates to mental health. Please take a moment to read the information below.

What's it all about?

Much research has examined interoception, the perception of the body's internal state (sensations like hunger, tiredness, feeling your heartbeat), using tasks of accuracy. Much less research attention has been paid to individual differences in one's attention to signals from our body and the environment. Usually, attention to these signals is measured using questionnaires that ask individuals to report on the extent to which people pay attention to bodily signals. The aim of this project is to provide a more ecologically valid measure of one's attention to signals from the body and from the environment, by assessing attention on multiple occasions.

We are recruiting adults between the ages of 18-60 with no hearing or visual impairments. For this study, participants will require a smartphone. In appreciation for your time, you will receive £15 or course credits (if you are an eligible RHUL psychology student signed up via the EMS system). You will also be offered a personalised report on how attentive you are over the course of a day.

What does the study involve?

If you choose to take part in the study, you will be invited to the RHUL psychology lab. In Part 1, you will be asked to complete some questionnaires that will assess your self-reported body awareness and mental health. You will also be asked to answer some demographic questions that will ask about your age, sex, gender identity, English language abilities, mental and physical health. You will then be asked to complete a screener task where your heartbeat will be sonified and will be out of sync with another auditory tone. You will use a dial on the application to advance or delay the auditory tones, until you perceive them as synchronous. You will then be asked to complete an interoception task where you will use a dial to advance or delay auditory tones that are out of sync with your heartbeat, until you perceive them as synchronous.

We will then ask you to download an application onto your smartphone. This mobile application will prompt you 10 times between the hours of 10-8pm, for six days, to answer questions; regarding what you are paying attention to and regarding your mood, stress and anxiety. This is Part 2 of the study.

After six days, you will be asked to attend the lab again for Part 3 of the study. You will be asked to complete the questionnaires on body awareness and mental health a second time. We will also ask you to complete the interoception task again as well as some questions about your experience of the survey.

The questionnaires and tasks in Part 1 will take approximately 40 minutes to an hour to complete. Part 2 involves answering questions 10 times a day for six days and will take approximately 2-3 minutes each time you receive a notification. You will be asked to complete a minimum of 80% of the daily surveys. The questionniares and interoception task in Part 3 will take approximately 40 minutes to an hour to complete in the RHUL lab. If you choose to take part, we will provide you with more instructions during Part 1 of the study. Tasks completed in Part 1 and 3 will be completed at the RHUL psychology lab.

Ethical Approval

The Royal Holloway Research Ethics Committee has approved this study following their reviewing procedures. We would like to stress that participation is entirely voluntary, and you may choose to withdraw from the study at any time without giving a reason. You are also free to withdraw your data after completing this study up until the point where the data is submitted for publication. To withdraw your data, please contact the researchers using the contact details below and provide your ID number so we can identify and withdraw your responses.

Important GDPR information:

Royal Holloway, University of London is the sponsor for this study and is based in the UK. We will be using information from you in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly.

The PIEL survey mobile application stores data only on your mobile device and you thus have control of your data until you decide to share it with us. You are free to delete this data at any time by deleting the application if you decide to withdraw from the study. The application does not gather any information from your device except for the time and date and your survey responses. When taking part, you will be asked to email your data file to the researchers at the end of the data collection phase. This data file will include your personal ID number and survey responses. To keep your data secure, we will ask you to email your responses to a dedicated mailbox that is accessed only by the researchers. Your survey responses in this file will not include response text (e.g., they will only include numbers).

The PAT task stores data in firebase which is ISO compliant. In this application your data will be identifiable only by the ID code that you will be asked to enter into the application. When completing this task, we will access your camera to detect your heartrate. Only your heartrate information and your adjustment of the phase between the auditory tones and your heartrate (as measured via the camera) will be recorded.

During the data collection, your email address will be stored with your participant ID in a password protected spreadsheet to allow the correct identification of your data between study Part 1 and Part 3. Your participant ID will not be attached to your response data and this file will be deleted upon completion of the study. Once the data collection phase of the project is complete, all data you provide will be transferred and stored securely on local servers. Email correspondence will be deleted upon the completion of the study. Upon completion of the study, your email address will be stored separately from your test data. If you withdraw from the study, we will delete all email correspondence and Qualtrics data, but you will be asked to delete the data from the PIEL mobile phone application as this is stored on your device until you chose to email this to us. You will have to right to withdraw your data up until the point of publication. Royal Holloway is designated as a public authority and in accordance with the Royal Holloway and Bedford New College Act 1985 and the Statutes which govern the College, we conduct research for the public benefit and in the public interest. Royal Holloway has put in place appropriate technical and organisational security measures to prevent your personal data from being accidentally lost, used or accessed in any unauthorised way or altered or disclosed.

Royal Holloway has also put in place procedures to deal with any suspected personal data security breach and will notify you and any applicable regulator of a suspected breach where legally required to do so. To safeguard your rights, we will use the minimum personally identifiable information possible (i.e., the email address you provide us). The lead researcher will keep your contact details confidential and will use this information only as required (i.e., to provide a summary of the study results if requested and/to send you your amazon voucher). The lead researcher will keep information about you and data gathered from the study for 5 years after the study has finished. Certain individuals from RHUL may look at your research records to check the accuracy of the research study. If the study is published in a relevant peer-reviewed journal, the anonymised data may be made available to third parties. Anonymised data may also be used for further studies.

The people who analyse the information will not be able to identify you. You can find out more about your rights under the GDPR and Data Protection Act 2018 by visiting https://www.royalholloway.ac.uk/about-us/more/governance-and-strategy/data-protection/ and if you wish to exercise your rights, please contact dataprotection@royalholloway.ac.uk

We respect the privacy and well-being of all participants and will keep information we collect in confidence. This means we will only tell those who have a right or need to know. Published reports based on these studies will not mention individuals. We will generate a unique ID code to identify your results.

We hope that you will be interested in taking part in our study. If you are happy to take part, please complete the additional consent form. This form will be kept separately from the responses you provide.

You may retain this information sheet for future reference and if you have any questions about the research, please do not hesitate to contact the team by email:

Researcher name: Ria Spooner
Email address: ria.spooner.2018@live.rhul.ac.uk

Researcher name: Rhea Clemente
Email address: rhea.clemente.2021@live.rhul.ac.uk

Researcher name: Nerea Irigoras Izagirre
Email address: nerea.irigorasizagirre.2021@live.rhul.ac.uk

To email my supervisor, Dr Jennifer Murphy, contact: Jennifer.murphy@rhul.ac.uk

Appendix F.

Participant consent form.

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Dr Jennifer Murphy
Lecturer
Jennifer.murphy@kcl.ac.uk
Email: Lara.Carr.2016@live.rhul.ac.uk

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Consent form

Interoceptive attention: an experience sampling study

Please read the following statements and tick the box if you agree, then sign below

- I have received a Research Information Sheet explaining the purpose of the study and have been given the opportunity to ask further questions. ☐

- I have received satisfactory responses to my questions and I understand that I can contact the researcher/s to ask further questions ☐

- I understand that the participation in this study is entirely voluntary. If I want to withdraw at any point during the research, I can do so without giving any reason. ☐

- I understand that my right to privacy will be respected at all times and the researchers will keep any information collected strictly confidential. ☐

- I understand that my anonymised data may be made available on the Open Science Framework website and that this can be accessed by anyone worldwide. ☐

I have read the consent form and agree to participate in the research being conducted by Ria Spooner, Rhea Clemente, Nerea Irigoras Izagirre and Dr Jennifer Murphy ☐

ID number (for researcher)…………………..

Name (block capitals)…………………………………………………………………..

Signature……………………………………………….. Date……………………………..

Appendix G.

Study debrief sheet.

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Dr Jennifer Murphy
Lecturer

Email: Jennifer.murphy@rhul.ac.uk

Study Debrief
Interoceptive attention: an experience sampling study

You have now completed all the aspects of this study. Many thanks for participating! Your contribution is vital in expanding our knowledge and furthering the potential of research efforts such as these.

The aim of this study was to develop an ecologically valid measure of one's attention to internal signals and to explore its association with stress and anxiety. The data will be used to examine the relationship between this new measure and existing self-report measures of body awareness. This study also examined accuracy in detecting the rhythm of one's heartbeat and we are interested in how this relates to the newly developed measure of attention to internal signals. As half of participants were asked about their attention to internal signals, and half were asked about attention to signals in the environment (e.g., auditory signals) we were also interested in determining whether asking about one's attention to internal signals altered individual's beliefs regarding their general disposition to focus on internal signals. Finally, using the questionnaire measures of personality and mental health, we were interested in whether the amount of attention people pay to their body is related to personality and mental health, including symptoms of anxiety and stress.

Once again, thank you for your participation in this research. We are extremely grateful and hope that you enjoyed the experience!

If you have any further questions feel free to ask them now, or to contact us using the details below.

Researcher name: Ria Spooner
Email address: ria.spooner.2018@live.rhul.ac.uk

Researcher name: Dr Jennifer Murphy
Email address: Jennifer.murphy@rhul.ac.uk

Researcher name: Rhea Clemente
Email address: rhea.clemente.2021@live.rhul.ac.uk

Researcher name: Nerea Irigoras Izagirre
Email address: nerea.irigorasizagirre.2021@live.rhul.ac.uk

If you want to talk about anything, related to this study or otherwise, the Samaritan's helpline is available 24 hours a day, seven days a week on: **116 123.**

Appendix H.

Wellbeing support sheet.

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Jennifer Murphy
Lecturer

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Research Wellbeing Support Sheet

Interoceptive Attention: An Experience Sampling Study

Thank you for completing the study questionnaires. We noticed that you scored highly on one or more of the questionnaires. This highlights possible concerns for us regarding your wellbeing. Please see below a list of resources, which we recommend accessing for further wellbeing support.

Royal Holloway, University of London Student Resources

Mental Health Practitioners
The Mental Health Practitioners provide mental health support to students who require support in primary care and, alongside the NHS GP surgery, form a common point of entry for triage, assessment, and referral (where needed) onto specialist mental health services. mentalhealth@royalholloway.ac.uk

Counselling
Counselling can provide an opportunity to explore any underlying issues that may be impacting your mood or overall wellbeing. https://intranet.royalholloway.ac.uk/students/help-support/counselling/home.aspx

Wellbeing Advisers Team
This team can support you with general wellbeing concerns and refer you to Royal Holloway's clinical and specialist services.
wellbeing@royalholloway.ac.uk

General Resources

Talking Therapies (NHS service)
Talking Therapies helps adults aged 18+ from Surrey with anxiety, depression, and stress. Talking Therapies attend the NHS GP Surgery on campus weekly during term time and by arrangement during the holiday period.
https://talkingtherapies.berkshirehealthcare.nhs.uk

Hub of Hope
The Hub of Hope can help you to identify local mental health services.
https://hubofhope.co.uk

Samaritans
This free helpline is available 24-hours a day, seven days a week on: 116 123.
https://www.samaritans.org

Shout
Shout can provide mental health support by offering free and confidential 24-hours a day, seven days a week text support on: 85258.
https://giveusashout.org

Surrey and Borders Mental Health Crisis Line
This mental health crisis line can be accessed 24-hours a day, 365 days a year for mental health advice and support on: 0800 915 4644.
www.sabp.nhs.uk/help

If you require immediate support or have any concerns regarding the mental health of someone else, we advise that you go to your nearest Accident & Emergency department, call 999 or speak to your GP.

If you have any questions, feel free to ask them now or contact us using the details below.

Supervisor name: Dr Jennifer Murphy
Email address: Jennifer.murphy@rhul.ac.uk

Researcher name: Ria Spooner
Email address: Ria.spooner.2018@live.rhul.ac.uk

Researcher name: Nerea Irigoras Izagirre
Email address: Nerea.irigorasizagirre.2021@live.rhul.ac.uk

Researcher name: Rhea Clemente
Email address: Rhea.clemente.2021@live.rhul.ac.uk

Appendix I.

IAS questionnaire as displayed in Qualtrics.

Below are several statements regarding how accurately you can perceive specific bodily sensations. Please rate on the scale how well you can perceive each specific signal. For example, if you often feel you need to urinate and then realise you do not need to when you go to the toilet you should rate your accuracy perceiving this bodily signal as low. Please only rate how well you can perceive these signals without using external cues, for example, if you can only perceive how fast your heart is beating when you measure it by taking your pulse this would not count as accurate internal perception.

I can always accurately perceive when my heart is beating fast.

- ○ Strongly Agree
- ○ Agree
- ○ Neither Agree nor Disagree
- ○ Disagree
- ○ Strongly Disagree

I can always accurately perceive when I am hungry.

- ○ Strongly Agree
- ○ Agree
- ○ Neither Agree nor Disagree
- ○ Disagree
- ○ Strongly Disagree

I can always accurately perceive when I am breathing fast.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I am thirsty.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I need to urinate.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I need to defecate.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I encounter different tastes. <p></p>

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I am going to vomit. <p></p>

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

I can always accurately perceive when I'm going to sneeze.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I'm going to cough.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am hot/cold.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am sexually aroused.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am going to pass wind.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am going to burp.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when my muscles are tired or sore.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am going to get a bruise.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when I am in pain.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when my blood sugar is low.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when someone is touching me affectionately rather than non-affectionately.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when something is going to be ticklish.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

I can always accurately perceive when something is going to be itchy.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

How much does your heart rate speed up when you feel nervous? To answer this question correctly, please do not tell us how much your heart rate speeds up when you are nervous. Please select that your heart rate changes 'not at all' when you get nervous.

- ◯ A great deal
- ◯ A lot
- ◯ A moderate amount
- ◯ A little
- ◯ Not at all

In this questionnaire we asked you to tell us how much accurately you can perceive specific bodily sensations. While you were completing the questionnaire, what did you think the term accuracy meant in this context? Please select one option that best describes your interpretation of the questionnaire.

- ◯ How much attention you pay to these sensations (e.g., how much they occupy your thoughts/mind, how much you think about these sensations, how much you monitor whether these signals are occurring or not (regardless of how well you can perceive them or how often they occur).

- ◯ How accurate you are at perceiving these sensations (e.g., how good you are at feeling/detecting them when they occur, how well you can tell them apart from other sensations when they occur, how precise you are at sensing them (regardless of how much you monitor them or how often they occur). lot

○ How often (frequently) or intensely these sensations actually occur in your body (e.g. how often your body is objectively cold, how often your muscles are objectively tired (regardless of how much you monitor them or how good you are at perceiving them).

○ None of the above. Please tell us...
____

Appendix J.

IATS questionnaire as displayed in Qualtrics.

Below are several statements regarding how much attention you pay to specific bodily sensations. Please rate on the scale how much attention you think you pay to each specific sensation. Think about how you feel during most situations in your daily life, rather than at a specific point in time. For example, if you often think about your heart beating, feeling hungry or needing the toilet then you would rate your attention to these sensations as high. In contrast, if you don't often think about your heart rate, how hungry you are or whether you need the toilet then you would rate your attention to these sensations as low. Please only rate how much attention you pay to these sensations regardless of how well you think you can perceive them. For example, if you often feel you need the toilet but when you go to the toilet you realise you don't need to you should still rate your attention to this signal as high. Do not worry about how often you think the sensation is truly happening inside your body – we would like to know how much of the time you pay attention to these sensations. The questions ask about your attention to feelings coming from inside your body. For example, if the question asks about temperature, it is referring to sensations you notice internally without using your hand to feel how warm your skin is, and if it asks about your heartbeat, it is referring to feelings you notice inside your body without taking your pulse.

Most of the time my attention is focused on whether my heart is beating fast.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I am hungry.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I am breathing fast.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I am thirsty or dehydrated.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I need to urinate.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I need to defecate.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time when I am eating, my attention is focused on different tastes.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I am nauseated or need to vomit.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I need to sneeze.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I need to cough.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on the temperature of my body (feeling hot or cold).

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I am sexually aroused.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I need to pass wind.

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Most of the time my attention is focused on whether I need to burp.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether my muscles are tired or sore.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on this completing this study. To prove this is true, select 'strongly agree'.

- ◯ Strongly agree
- ◯ Agree
- ◯ Neither agree nor disagree
- ◯ Disagree
- ◯ Strongly disagree

Most of the time my attention is focused on whether I am in pain after I am hurt or injured.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether I am in pain (that is not caused by injury).

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time my attention is focused on whether my blood sugar is low.

- ◯ Strongly Agree
- ◯ Agree
- ◯ Neither Agree nor Disagree
- ◯ Disagree
- ◯ Strongly Disagree

Most of the time when someone is touching me, my attention is focused on whether it is pleasant/affectionate.

- ○ Strongly Agree
- ○ Agree
- ○ Neither Agree nor Disagree
- ○ Disagree
- ○ Strongly Disagree

Most of the time my attention is focused on whether touch or materials feel ticklish on my body.

- ○ Strongly Agree
- ○ Agree
- ○ Neither Agree nor Disagree
- ○ Disagree
- ○ Strongly Disagree

Most of the time my attention is focused on whether my body feels itchy.

- ○ Strongly Agree
- ○ Agree
- ○ Neither Agree nor Disagree
- ○ Disagree
- ○ Strongly Disagree

In this questionnaire we asked you to tell us how much attention you pay to specific bodily sensations. While you were completing the questionnaire, what did you think the term attention meant in this context? Please select one option that best describes your interpretation of the questionnaire.

- ○ How much attention you pay to these sensations (e.g., how much they occupy your thoughts/mind, how much you think about these sensations, how much you monitor whether these signals are occurring or not (regardless of how well you can perceive them or how often they occur).

- ○ How accurate you are at perceiving these sensations (e.g., how good you are at feeling/detecting them when they occur, how well you can tell them apart from other sensations when they occur, how precise you are at sensing them (regardless of how much you monitor them or how often they occur). lot

- ○ How often (frequently) or intensely these sensations actually occur in your body (e.g. how often your body is objectively cold, how often your muscles are objectively tired (regardless of how much you monitor them or how good you are at perceiving them).

- ○ None of the above. Please tell us...
____

Appendix K.

ESM survey questions for the interoceptive group.

1. Next you will be asked to rate your attention to internal signals from your body. Internal signals include things like gastric sensations (hunger, nausea, fullness, digestion), tiredness, your heartbeat, breathing, pain, muscle aches, itch or tickle. Do you understand?

    |Yes |No

2. You will be asked to rate your attention to internal signals regardless of whether the signal is present (e.g., thinking about whether you need the toilet, even if you don't need the toilet, would still count as paying attention to an internal signal). Do you understand?

    |Yes |No

3. In the last 5 minutes, how much of the time were you paying attention to internal signals? Please indicate using the response options below.

    |All of the last 5 minutes|Most of the last 5 minutes|About half of the last 5 minutes|Some of the last 5 minutes|None of the last 5 minutes

4. In the last 5 minutes, how have you been feeling emotionally? Please indicate using the response options below.

    |Very positive|Positive|Neutral|Negative|Very Negative

5. How stressed have you felt in the last 5 minutes?

    |Not at all stressed|Slightly stressed|Moderately stressed|Very stressed|Extremely stressed

6. How stressful was the activity or event you were involved with in the last 5 minutes?

    |Not at all stressful|Slightly stressful|Moderately stressful|Very stressful|Extremely stressful

7. Please select the option that shows how anxious you feel at the moment.

   |1 - You are feeling not at all anxious at the moment |2|3 - You are feeling moderately anxious |4|5 - You are feeling the most anxious you could ever imagine.

ESM survey question for the auditory group.

1. Next you will be asked to rate your attention to auditory signals in your environment. Auditory signals include things like listening to music, the television or a podcast as well as things in the background like birds signing, transport noises, the sound of people talking. Do you understand?

   |Yes |No

2. You will be asked to rate your attention to auditory signals regardless of whether the signal is present (e.g., thinking about whether you heard a noise, even if you realise there was no noise, would still count as paying attention to an auditory signal). Do you understand?

   |Yes |No

3. In the last 5 minutes, how much of the time were you paying attention to auditory signals? Please indicate using the response options below.

   |All of the last 5 minutes|Most of the last 5 minutes|About half of the last 5 minutes|Some of the last 5 minutes|None of the last 5 minutes

4. In the last 5 minutes, how have you been feeling emotionally? Please indicate using the response options below.

   |Very positive|Positive|Neutral|Negative|Very Negative

5. How stressed have you felt in the last 5 minutes?

   |Not at all stressed|Slightly stressed|Moderately stressed|Very stressed|Extremely stressed

6. How stressful was the activity or event you were involved with in the last 5 minutes?

    |Not at all stressful|Slightly stressful|Moderately stressful|Very stressful|Extremely stressful

7. Please select the option that shows how anxious you feel at the moment.

    |1 - You are feeling not at all anxious at the moment |2|3 - You are feeling moderately anxious |4|5 - You are feeling the most anxious you could ever imagine.

Appendix L.

DASS questionnaire as displayed in Qualtrics.

Please read each statement and choose an option to indicate how much the statement applied to you over the past week. There are no right or wrong answers. Do not spend too much time on any statement.

I found it hard to wind down

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I was aware of dryness of my mouth

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I couldn’t seem to experience any positive feeling at all

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I experienced breathing difficulty (e.g. excessively rapid breathing, breathlessness in the absence of physical exertion)

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I found it difficult to work up the initiative to do things

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I tended to over-react to situations

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I experienced trembling (e.g. in the hands)

- Did not apply to me at all
- Applied to me to some degree, or some of the time
- Applied to me to a considerable degree or a good part of time
- Applied to me very much or most of the time

I felt that I was using a lot of nervous energy

- Did not apply to me at all
- Applied to me to some degree, or some of the time
- Applied to me to a considerable degree or a good part of time
- Applied to me very much or most of the time

I was worried about situations in which I might panic and make a fool of myself

- Did not apply to me at all
- Applied to me to some degree, or some of the time
- Applied to me to a considerable degree or a good part of time
- Applied to me very much or most of the time

I felt that I had nothing to look forward to

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I found myself getting agitated

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I found it difficult to relax

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I felt down-hearted and blue

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I was intolerant of anything that kept me from getting on with what I was doing

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I felt I was close to panic

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I was unable to become enthusiastic about anything

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I felt I wasn't worth much as a person

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I felt that I was rather touchy

- ○ Did not apply to me at all
- ○ Applied to me to some degree, or some of the time
- ○ Applied to me to a considerable degree or a good part of time
- ○ Applied to me very much or most of the time

I was aware of the action of my heart in the absence of physical exertion (e.g. sense of heart rate increase, heart missing a beat)

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

When asked what colour your mood is, please enter 'pink' in the text box below.

Based on the text above, what colour is your mood? Please write your response in the text box below

____

I felt scared without any good reason

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

I felt that life was meaningless

- ◯ Did not apply to me at all
- ◯ Applied to me to some degree, or some of the time
- ◯ Applied to me to a considerable degree or a good part of time
- ◯ Applied to me very much or most of the time

Appendix M.

SRRS questionnaire as displayed in Qualtrics.

Please select all the life events that have happened to you during the previous year.

Death of spouse

- ○ Yes
- ○ No

Divorce

- ○ Yes
- ○ No

Marital separation

- ○ Yes
- ○ No

Jail term

- ○ Yes
- ○ No

Death of close family member

- ◯ Yes
- ◯ No

Personal injury or illness

- ◯ Yes
- ◯ No

Marriage

- ◯ Yes
- ◯ No

Fired at work

- ◯ Yes
- ◯ No

Marital reconciliation

- ◯ Yes
- ◯ No

Retirement

- ◯ Yes
- ◯ No

Change in health of family member

- ◯ Yes
- ◯ No

Pregnancy

- ◯ Yes
- ◯ No

Sex difficulties

- ◯ Yes
- ◯ No

Gain of a new family member

- ◯ Yes
- ◯ No

Business readjustment

- ◯ Yes
- ◯ No

Change in financial state

- ◯ Yes
- ◯ No

Death of a close friend

- ◯ Yes
- ◯ No

Change to a different line of work

- ◯ Yes
- ◯ No

Change in number of arguments with partner

- ◯ Yes
- ◯ No

If you are still paying attention, select 'no'

- Yes
- No

A large mortgage or loan

- Yes
- No

Foreclosure of mortgage or loan

- Yes
- No

Change in responsibilities at work

- Yes
- No

Son or daughter leaving home

- Yes
- No

Trouble with in-laws

- ◯ Yes
- ◯ No

Outstanding personal achievement

- ◯ Yes
- ◯ No

Partner begins or stops work

- ◯ Yes
- ◯ No

Begin or end school/college

- ◯ Yes
- ◯ No

Change in living conditions

- ◯ Yes
- ◯ No

Revision of personal habits

- ◯ Yes
- ◯ No

Trouble with boss

- ◯ Yes
- ◯ No

Change in work hours or conditions

- ◯ Yes
- ◯ No

Change in residence

- ◯ Yes
- ◯ No

Change in school/college

- ◯ Yes
- ◯ No

Change in recreation

- ○ Yes
- ○ No

Change in church activities

- ○ Yes
- ○ No

Change in social activities

- ○ Yes
- ○ No

A moderate loan or mortgage

- ○ Yes
- ○ No

Change in sleeping habits

- ○ Yes
- ○ No

Change in number of family get-togethers

- ◯ Yes
- ◯ No

Change in eating habits

- ◯ Yes
- ◯ No

Vacation

- ◯ Yes
- ◯ No

Select 'yes' if you are paying attention

- ◯ Yes
- ◯ No

Christmas

- ◯ Yes
- ◯ No

Minor violations of the law

- ◯ Yes
- ◯ No

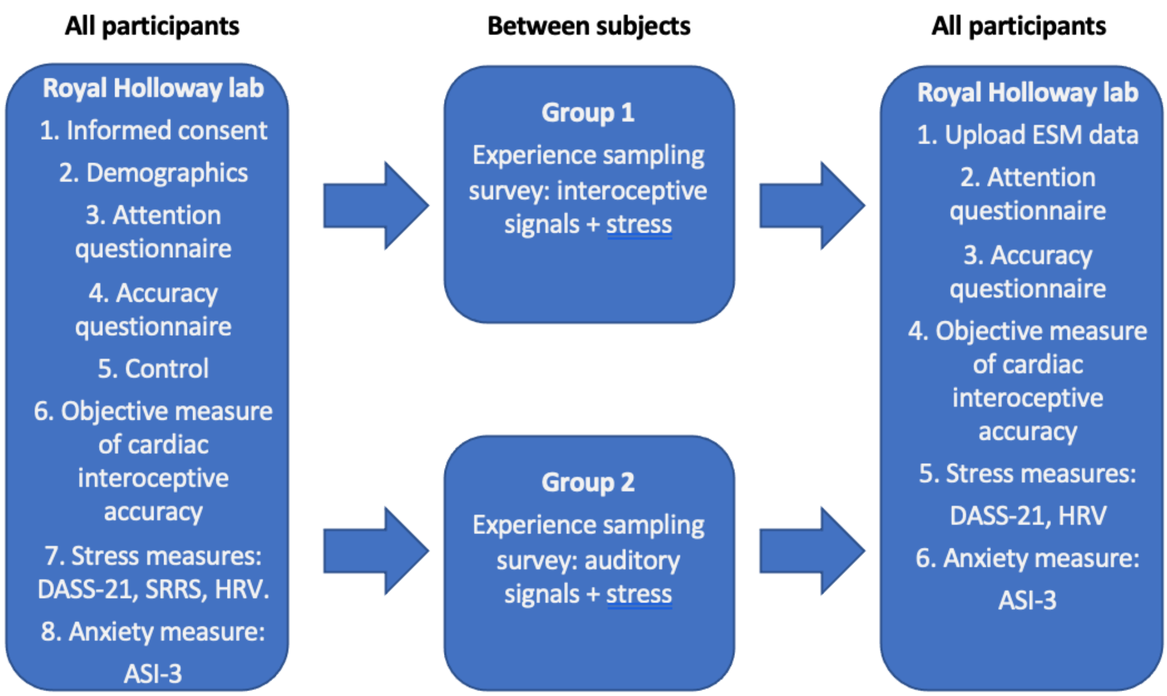
Appendix M.

Study design and all included measures.

This study was part of a larger study that included additional measures. First, anxiety measures were employed by including the DASS-21 anxiety subscale, the Anxiety Sensitivity Index-3 (ASI-3) questionnaire and an ESM question to assess anxiety (see Appendix K). Second, trait-based measures of interoception (IAS and IATS) and the objective measure of cardiac interoceptive accuracy (PAT) were administered in the second testing session to control for the effects of the ESM on measures of interoception. Finally, self-report (DASS-S) and physiological (HRV) measures of stress were also administered in the second testing session to control for the effects of ESM on measures of stress. However, the additional measures of interoception and stress were not included in the final analysis due to constraints regarding the size of the study. Therefore, only baseline measures of stress and interoception were included in the present study, and the additional measures will be reported elsewhere.

Figure 24.

Full study design and procedure.



Appendix N.

Correlation analyses between trait stress, trait interoception and objective interoception measures divided by sex.

Table 15.

Correlation matrix for males.

Measure	1	2	3	4	5
1. Physiological stress	-				
2. Self-reported stress	.086	-			
3. IATS	-.075	.346*	-		
4. IAS	.023	-.347*	.167	-	
5. PAT	.147	-.098	0	.043	-
6. Control	-.091	.297	-.139	-.456**	-.091

* Significant at 0.05 (2-tailed)

Abbreviations: IATS Interoceptive Attention Scale, IAS Interoceptive Accuracy Scale, PAT Phase Adjustment Task.

Table 16.

Correlation matrix for females.

Measure	1	2	3	4	5
1. Physiological stress	-				
2. Self-reported stress	.152	-			
3. IATS	-.338*	.263	-		
4. IAS	-.014	-.091	.159	-	
5. PAT	.066	.057	-.049	-.329*	-
6. Control	-.094	.095	-.006	-.233	.084

* Significant at 0.05 (2-tailed)

Abbreviations: IATS Interoceptive Attention Scale, IAS Interoceptive Accuracy Scale, PAT Phase Adjustment Task.

Appendix O.

Fixed effect model of state interoception and trait and state stress measures divided by sex.

Table 17.

Fixed effect model of state interoception and trait and state stress for males.

Measure	**Group**	**β**	**95% CI**	**SE**	**df**	**t**	**p**
Physiological stress (PCA Factor 1)	Interoceptive	-0.197	-0.652 – 0.257	0.212	14.008	-0.93	0.368
	Auditory	-0.085	-0.459 – 0.288	0.178	18.818	-0.477	0.639
Self-reported stress (PCA Factor 2)	Interoceptive	-0.143	-0.808 – 0.521	0.31	14.004	-0.463	0.651
	Auditory	0.179	-0.165 – 0.523	0.164	19.128	1.091	0.289
State perceived stress (ESM item 5)	Interoceptive	0.166	0.089 – 0.243	0.039	1018.853	4.214	<0.001
	Auditory	-0.087	-0.182 – 0.007	0.048	1152.407	-1.808	0.071
State stressors (ESM item 6)	Interoceptive	0.130	0.053 – 0.207	0.039	1009.075	3.310	<0.001
	Auditory	0.013	-0.085 – 0.111	0.05	1163.004	0.264	0.792

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, PCA Principal Component Analysis, ESM Experience Sampling Method.

Table 18.

Fixed effect model of state interoception and trait and state stress for females.

Measure	Group	β	95% CI	SE	df	t	p
Physiological stress (PCA Factor 1)	Interoceptive	0.061	-0.268 – 0.39	0.159	22.923	0.386	0.703
	Auditory	0.117	-0.227 – 0.462	0.165	19.418	0.71	0.486
Self-reported stress (PCA Factor 2)	Interoceptive	0.309	-0.062 – 0.68	0.179	22.968	1.724	0.098
	Auditory	0.121	-0.208 – 0.45	0.157	19.407	0.769	0.451
State perceived stress (ESM item 5)	Interoceptive	0.102	0.024 – 0.181	0.04	1445.136	2.551	0.011
	Auditory	0.008	-0.069 – 0.084	0.039	1154.872	0.2	0.842
State stressors (ESM item 6)	Interoceptive	0.098	0.015 – 0.181	0.042	1449.080	2.308	0.021
	Auditory	0.005	-0.076 – 0.085	0.041	1181.25	0.112	0.911

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, PCA Principal Component Analysis, ESM Experience Sampling Method.

Appendix P.

Fixed effect model of state perceived stress and trait interoceptive measures divided by sex.

Table 19.

Fixed effect model of state perceived stress and trait interoceptive measures for males.

Measure	Group	β	95% CI	SE	df	t	p
IAS	Interoceptive	-0.009	-0.039 – 0.021	0.014	13.217	-0.646	0.529
	Auditory	-0.002	-0.034 – 0.03	0.015	16.934	-0.104	0.919
IATS	Interoceptive	0.002	-0.014 – 0.018	0.007	14.943	0.239	0.814
	Auditory	0.006	-0.017 – 0.03	0.011	15.952	0.548	0.591
PAT	Interoceptive	-0.734	-2.94 – 1.471	1.013	12.076	-0.725	0.482
	Auditory	-0.61	-1.657 – 0.436	0.501	19.906	-1.217	0.238
Control	Interoceptive	3.157	-3.212 - 9.527	2.992	15.206	1.055	0.308
	Auditory	0.999	-1.092 – 3.089	1.002	19.837	0.997	0.331

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, IAS Interoceptive Accuracy Scale, IATS Interoceptive Attention Scale, PAT Phase Adjustment Task.

Table 20.

Fixed effect model of state perceived stress and trait interoceptive measures for females.

Measure	Group	β	95% CI	SE	df	t	p
IAS	Interoceptive	0.001	-0.433 – 3.779	0.013	26.076	0.108	0.915
	Auditory	-0.003	-0.021 – 0.016	0.009	19.55	-0.322	0.751
IATS	Interoceptive	0.017	-0.009 – 0.042	0.012	25.035	1.356	0.187
	Auditory	0.001	-0.016 – 0.018	0.008	21.239	0.112	0.912
PAT	Interoceptive	0.16	-1.424 – 1.745	0.771	26.114	0.208	0.837
	Auditory	0.8	-0.405 – 2.005	0.575	18.705	1.391	0.181
Control	Interoceptive	-1.362	-4.231 – 1.507	1.387	23.16	-0.982	0.336
	Auditory	-0.25	-1.277 – 0.777	0.495	22.069	-0.504	0.619

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, IAS Interoceptive Accuracy Scale, IATS Interoceptive Attention Scale, PAT Phase Adjustment Task.

Appendix Q.

Fixed effect model of state perceived stressors and trait interoceptive measures divided by sex.

Table 21.

Fixed effect model of state perceived stressors and trait interoceptive measures for males.

Measure	Group	β	95 % CI	SE	df	t	p
IAS	Interoceptive	0.109	-0.039 – 0.012	0.012	13.323	-1.158	0.267
	Auditory	-0.005	-0.024 – 0.015	0.009	16.743	-0.497	0.626
IATS	Interoceptive	-0.003	-0.018 – 0.011	0.007	14.868	-0.498	0.626
	Auditory	0.005	-0.01- 0.02	0.007	15.86	0.753	0.462
PAT	Interoceptive	-0.823	-2.66 – 1.015	0.844	12.057	-0.975	0.349
	Auditory	-0.697	-1.353 - -0.04	0.315	19.714	-2.215	0.039
Control	Interoceptive	3.217	-2.227 – 8.661	2.558	15.226	1.258	0.227
	Auditory	0.761	-0.955 – 2.477	0.823	20.171	0.925	0.366

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, IAS Interoceptive Accuracy Scale, IATS Interoceptive Attention Scale, PAT Phase Adjustment Task.

Table 22.

Fixed effect model of state perceived stressors and trait interoceptive measures for females.

Measure	Group	β	95 % CI	SE	df	t	p
IAS	Interoceptive	0.002	-0.024 – 0.028	0.013	26.15	0.191	0.85
	Auditory	0	-0.015 – 0.014	0.007	19.615	-0.054	0.957
IATS	Interoceptive	0.013	-0.012 – 0.038	0.012	25.077	1.049	0.304
	Auditory	0.002	-0.012 – 0.015	0.007	21.467	0.284	0.779
PAT	Interoceptive	-0.182	-1.679 – 1.315	0.729	26.184	-0.25	0.805
	Auditory	0.628	-0.407 - 1.663	0.494	18.765	1.27	0.22
Control	Interoceptive	-1.593	-4.313 – 1.127	1.316	23.209	-1.211	0.238
	Auditory	-0.217	-1.176 – 0.743	0.463	22.015	-0.468	0.644

Abbreviations: β Beta, CI Confidence Interval, SE Standard Error, df degrees of freedom, t Student's t distribution, p probability value, IAS Interoceptive Accuracy Scale, IATS Interoceptive Attention Scale, PAT Phase Adjustment Task.